



UNIVERSITY OF PISA  
COMPUTER SCIENCE

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## Machine Learning

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Based on Prof. Alessio Micheli's lectures

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## Notes

These notes are intended only as support for the study of the subject and as slides side notes. They do not cover the whole program but only a part. In order to compensate for the missing parts, we recommend the use of slides and books provided by Prof. Micheli for each topic.

We hope these notes will help future students and if you find any mistakes or want to help extend these notes, feel free to do so in the GitHub repo.

**What you will find here:** Introduction to ML, Linear Model and K-NN, Neural Networks, Validation, Statistical Learning Theory (STL).

**What's missing:** Concept Learning, SVM, Bias Variance, Deep Learning (CNN, Deep, Rand), SOM, Bayes Learning, RNN, SDL.

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# 1 Introduction

The problem of learning is arguably at the very core of the problem of intelligence, both biological and artificial

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Poggio, Shelton, AI Magazine 1999

## 1.1 What is ML

The field of **machine learning** is concerned with the question of how to construct computer programs that automatically improve with experience.

In recent years many successful machine learning applications have been developed, ranging from data-mining programs that learn to detect fraudulent credit card transactions, to information-filtering systems that learn users' reading preferences, to autonomous vehicles that learn to drive on public highways.

At the same time, there have been important advances in the theory and algorithms that form the foundations of this field. Machine learning draws on concepts and results from many fields, including statistics, artificial intelligence, philosophy, information theory, biology, cognitive science, computational complexity, and control theory.

**Machine Learning** has emerged as an area of research combining the aims of *creating computers that could learn* (AI - Build adaptive/personalized intelligent systems) and new powerful *adaptive/statistical tools* with rigorous foundation in computational science for data analysis.

**Learning** is the major challenge and a strategic way to provide intelligence into the systems.

**Definition 1.1** (Learning Computer)

*A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.*

The ML studies and proposes methods to build (infer) a model (dependencies / functions / hypotheses) from examples of observed data

- That fits the known examples.
- Able to generalize with reasonable accuracy for new data (according to verifiable results, under statistical and computational conditions and criteria).
- Considering the expressiveness and algorithmic complexity of the models and learning algorithms.

**Example 1.1** (Inferring general functions from known data)

*Two famous examples of ML tasks:*

- *Handwriting Recognition: x (Data from pen motion) and f(x) (Letter of the alphabet)*
- *Face recognition: x (Bitmap picture of person's face) f(x) (Name of the person)*

So we have some opportunity (if useful) and awareness (needs and limits):

**Utility of predictive models: (in the following cases):**

- no (or poor) theory (or knowledge to explain the phenomenon)
- uncertain, noisy or incomplete data (which hinder formalization of solutions)

**Requests:**

- source of training experience (representative data)
- tolerance on the precision of results

## 1.2 Overview: Components of a ML System

Main components of a ML system, Framework as a guide to the key design choices:



Figure 1.1: Components of a ML system

### 1.3 Data

The data represent the available facts (experience). Representation problem: to capture the structure of the analyzed objects. **Type:** Flat, Structured, ...

We will generally use flat data:

E.g. **Flat DATA** (attribute-value language): fixed-size vectors of properties (features), single table of tuple (measurements of the objects), Attributes can be discrete or continuous

Fruits	Weight	Cost \$	Color	Bio	
Fruit 1 (lemon)	2.1	0.5	y	1	Attributes (discrete/continuous)
Fruit 2 (apple)	3.5	0.6	r	?	

■ Categorical/continuous, missing data...
 ■ Preprocessing: e.g. Variable scaling, encoding\*, selection...

Of course Data type can be different, usually there is a Data Preprocessing step, e.g. Variable scaling, encoding, selection... For this step, see in Data Mining: *Data Understanding* and *Data Preparation*.

#### Example and terminologies

Let's see a example with some Medical records in the flat case:

Patients	Age	Smoke	Sex	Lab Test	
Pat 1	101	0.8	M	1	Attributes (discrete/continuous)
Pat 2	30	0.0	F	?	

- Each row ( $\mathbf{x}$ , vector): example, pattern, instance, sample,...
- Dimension of data set: number of examples  $l$
- Dimension (of  $\mathbf{x}$ ): number of features  $n$
- If we will index the features/inputs/variables by  $j$  : variable  $x_j$  is (typically) the j-th feature/property/attribute/element of  $\mathbf{x}$ .

but may be to simplify we need to use subscript index for other meanings

- $\mathbf{x}_p$  is (typically) the p-th pattern/example/raw ( $\mathbf{x}$  bold is a vector)
- $x_{pj}$  for example can be the attribute j of the pattern p

#### DATA Encoding

For the **Flat case** we can have **Numerical encoding for categories** e.g.:

- 0/1 (or -1/+1) for 2 classes
- 1,2,3... Warning: grade of similarity (1 vs 2 or 3): useful for “order categorical” variables (e.g small, medium, large)

- 1-of-k (or 1-hot) encoding: useful for symbols

<b>A</b>	1	0	0
<b>B</b>	0	1	0
<b>C</b>	0	0	1

Useful both for input or output variables

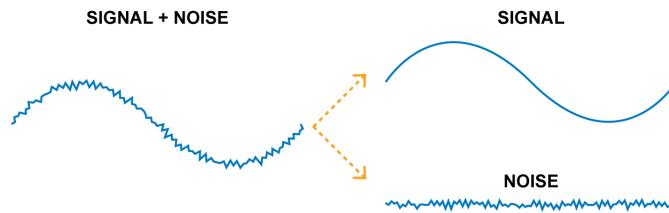
This is useful because the scalar product between two vectors representing two coded symbols is zero.  
The vectors are orthogonal, this implies that there is no relation between the category symbols.

Another types of Data:

E.g. **Structures DATA**: Sequences (lists), trees, graphs, Multi-relational data (table) (in DB)  
Examples: images, microarray, temporal data, strings of a language, DNA e proteins, hierarchical relationships, molecules, hyperlink connectivity in web pages, ...

### Further terminologies

- **Noise**: addition of external factors to the stream of target information (signal); due to randomness in the measurements, not due to the underlying law: e.g. Gaussian noise



- **Outliers**: are unusual data values that are not consistent with most observations (e.g. due to abnormal measurements errors). Some operation can be perform: outlier detection and preprocessing (removal) or we have to use some Robust Modeling Methods.
- **Feature selection**: selection of a small number of informative features: it can provide an optimal representation for a learning problem

## 1.4 Task

The task defines the purpose of the application: Knowledge that we want to achieve? Which is the helpful nature of the result? What information are available?

There are two main categories of tasks:

- **Predictive** (Classification, Regression): function approximation (build a function from examples)



- **Descriptive** (Cluster Analysis, Association Rule): find subsets or groups of unclassified data

We can usually divide tasks in *Supervised Learning* and *Unsupervised Learning*:

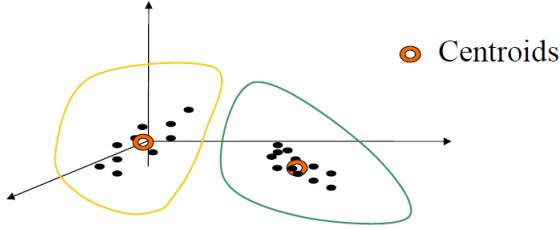


Figure 1.2: An Example of Clustering, Partition of data into clusters (subsets of “similar” data)

## Supervised Learning

Given a training example as  $\langle \text{input}, \text{output} \rangle = \langle \mathbf{x}, d \rangle$  (**labeled example**) for an unknown function  $f$ , the aim is to find a *good* approximation to  $f$  (an **hypothesis**  $h$  that can be used for prediction on unseen data  $\mathbf{x}'$ ).

Target  $d$  (or  $t$  or  $y$ ) is given by the teacher according to a  $f(\mathbf{x})$  (unknown function),  $d$  is usually a numerical/categorical label:

- *Classification*: discrete value outputs:

$$f(\mathbf{x}) \in \{1, 2, \dots, K\} \text{ classes (discrete-valued function).}$$

- *Regression*: real continuous output values (approximate a real-valued target function)

Note: we can use the same model, we only have to change the domain of the output (Unified vision thanks to the formalism of func. approximation).

## Unsupervised Learning

Given a training set of **unlabeled data**  $\langle \mathbf{x} \rangle$ , the aim is to find a *natural groupings* in the set. Some tasks are:

- Clustering, see figure 1.2
- Dimensionality reduction/ Visualization/Preprocessing
- Modeling the data density

### 1.4.1 Classification

(Supervised) Classification: Patterns (feature vectors) are seen as members of a class and the goal is to assign the patterns observed classes (label).

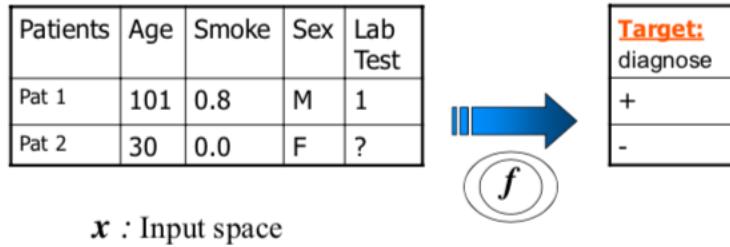
So, the aim is to find a *good* approximation to  $f(\mathbf{x})$  (an **hypothesis**  $h$ ) that can be used to return a prediction on unseen data  $\mathbf{x}'$  and tell what class  $\mathbf{x}'$  belongs to, see figure 1.3.

If the number of classes is 2, the approximation of  $f(\mathbf{x})$  is a boolean function (binary classification, **concept learning**), instead if the number of classes is greater than 2, we talk about *multi-class problem* ( $C_1, C_2, \dots, C_k$ ).

The classification may be viewed as the allocation of the input space in decision regions (e.g. 0/1) and we want to find a linear separator on an instance space  $\mathbf{x} = (x_1, x_2)$  in  $\mathbb{R}^2$  where  $f(\mathbf{x}) = 0/1$  (or  $-1/+1$ ).

In figure 1.4a we can see an hyperplane which separates the points and this is a hypothesis  $h(x)$  (an approximation to  $f(\mathbf{x})$ ) found in the space of hypotheses  $H$  (set of dichotomies induced by hyperplanes), see figure 1.5.

From DATA to TASK (e.g. classification)



Terminology in statistics:

- Inputs are the "independent variables"
- Outputs are the "dependent variables" or "responses"

Figure 1.3: A classification task: we want to get an approximation to  $f(\mathbf{x})$ , we want to understand if future patients are positive or negative to a certain diagnosis

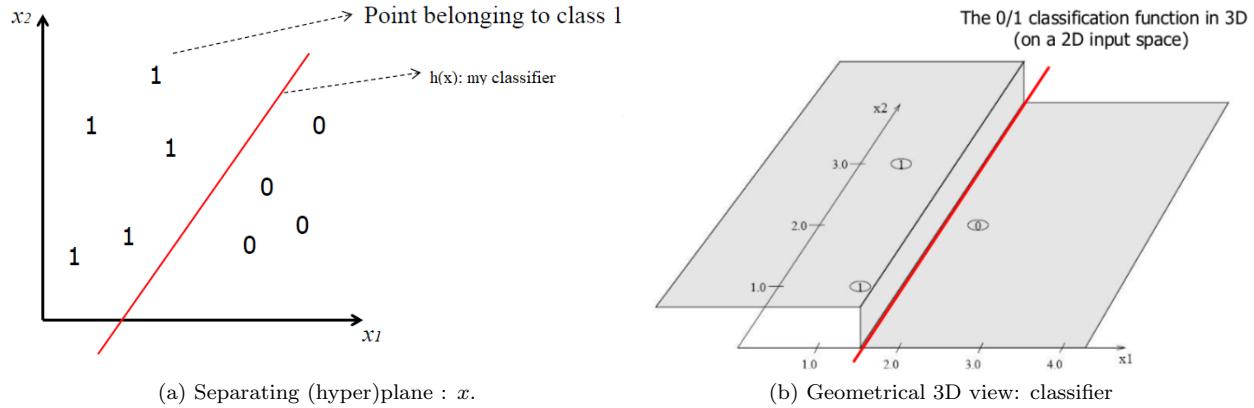


Figure 1.4: An example of classification, that use a linear separator on the instance space.

$$\mathbf{w}\mathbf{x} + w_0 = w_1x_1 + w_2x_2 + w_0 = 0$$

$$h(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{w}\mathbf{x} + w_0 \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

or

$$h(\mathbf{x}) = \text{sign}(\mathbf{w}\mathbf{x} + w_0)$$

Linear threshold unit (LTU)  
Indicator functions

Figure 1.5: Hyperplanes classifier

### 1.4.2 Regression

Process of estimating of a real-value function on the basis of finite set of noisy samples (supervised task), we have known pairs  $(x, f(x) + \text{random noise})$ .

**Goal Task:** find a function that approximate the data in figure 1.6:

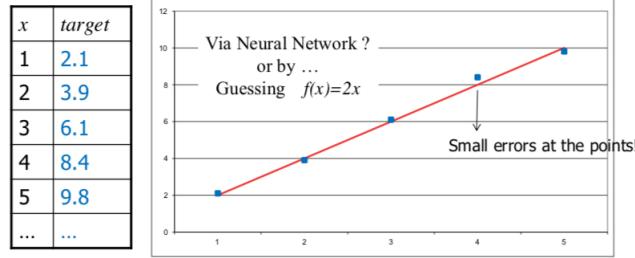
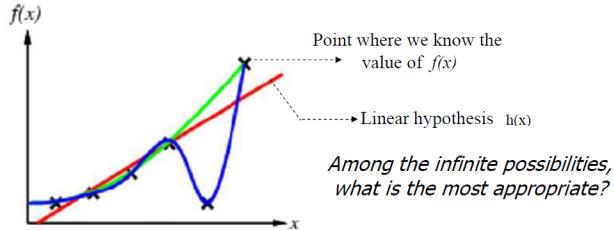


Figure 1.6: A example of regression

Regression:  $x$  = variables (e.g real values),  $(f(x) + \text{random noise})$  real values that we know, so we want to find a curve that best fit the data: *curve fitting*. An example of curve fitting is a **linear hypothesis**:



$h_w(x) = w_1x + w_0 = 0.2x - 0.4$  but we have to choose the best one with some criteria.

### 1.4.3 Other Tasks

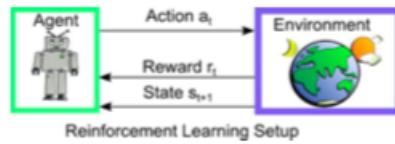
There are other types that we will not discuss, like:

- **Dimensionality reduction** (in unsupervised Learning)

$$\langle x_1, x_2, \dots, x_n \rangle \rightarrow \langle x_1, x_2, \dots, x_m \rangle \text{ with } m < n$$

- **Reinforcement Learning** (learning with right/wrong critic): This is usually a supervised learning task with some police!

- **Adaptation in autonomous systems**
- “the algorithm learns a policy of how to act given an observation of the world. Every action has some impact in the environment, and the environment provides feedback that guides the learning algorithm”.
- Toward decision-making aims
- Useful in modern AI



- **Semi-supervised learning:** combines both labeled and unlabeled examples to generate an appropriate function or classifier.

## 1.5 Models

The aim is to capture/describes the relationships among the data (on the basis of the task) by a “language”. The “language” is related to the representation used to get knowledge. It defines the class of functions that the learning machine can implement (*hypothesis space*).

E.g. set of functions  $h(x, w)$ , where  $w$  is the (abstract) parameter.

**Definition 1.2** (Model main terms)

*The terminologies associated to the model is:*

- **Training examples** (supervised learning):  
An example of the form  $(x, f(x))$ .  $x$  is usually a vector of features,  $t = f(x)$  is called the target value.
- **Target function:** The true function  $f$  (that we don't have! we want to approximate it!)
- **Hypothesis:** A proposed function  $h$  believed to be similar to  $f$ . An expression in a given language that describes the relationships among data.
- **Hypotheses space ( $H$ ):** The space of all hypotheses that can, in principle be output by the learning algorithm (set of functions  $h(x, w)$ , where  $w$  is the parameter), this is a Hilbert Space.

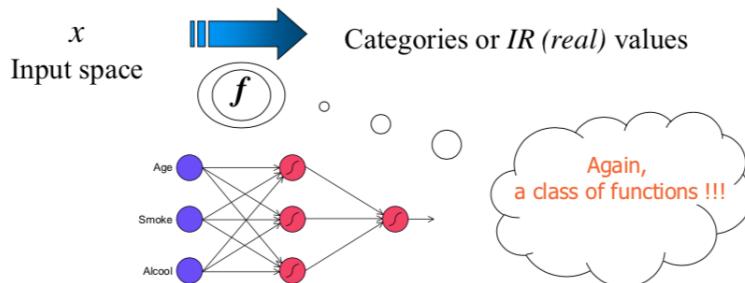
Some models are shown here:

Just to have a preview of different *representation* of hypothesis

(because you already know the language of equations, logic, probability):

- **Linear models** (representation of  $H$  defines a continuously parameterized space of potential hypothesis);  
each assignment of  $w$  is a different hypothesis, e.g:
  - $h(\mathbf{x}) = \text{sign}(\mathbf{w}\mathbf{x} + w_0)$  binary classifier
  - $h_w(\mathbf{x}) = w_1x_1 + w_0$  E.g.  $h_w(\mathbf{x}) = 2x_1 + 150$  simple linear regression
- **Symbolic Rules:** (hypothesis space is based on discrete representations);  
different rules are possible , e.g:
  - if  $(x_1=0) \text{ and } (x_2=1)$  then  $h(\mathbf{x})=1$  binary classifier
  - else  $h(\mathbf{x})=0$
- **Probabilistic models:** estimate  $p(x,y)$
- K Nearest neighbor regression: Predict mean  $y$  value of nearest neighbors (memory-based)

Another example: we will see a **neural networks**, beyond the neurobiological inspiration, as a computational model for the treatment of data, capable of approximating complex (non-linear) relationships between inputs and outputs.



### 1.5.1 Paradigms and methods (Languages for H)

- Symbolics and Rule-based (or discrete H)
  - Conjunction of literals, Decision trees (propositional rules)
  - Inductive grammars, Evolutionary algorithms, ...
  - Inductive Logic Programming (first order logic rules)
- Sub-symbolic (or continuous H)
  - Linear discriminant analysis, Multiple Linear Regression, LTU
  - Neural networks
  - Kernel methods (SVMs, gaussian kernels, spectral kernels, etc)
- Probabilistic/Generative
  - Traditional parametric models (density estimation, discriminant analysis, polynomial regression, ...)
  - Graphical models: Bayesian networks, naive Bayes, PLSA, Markov models, Hidden Markov models, ...
- Instance-based
  - Nearest neighbor

### 1.5.2 How many models?

**Theorem 1.1** (No Free Lunch Theorem)

*There is no universal “best” learning method (without any knowledge, for any problems,...): if an algorithm achieves superior results on some problems, it must pay with inferiority on other problems. In this sense there is no free lunch.*

**NOTE:** However, not all the models are equivalent: (instead of assuming a specific form for the target function (parametric models in classical Statistics)).

The course provide:

- A set of models.
- The critical instrument to compare them.

The core of ML is on flexible approaches that can in principle approximate arbitrary functions (universal approximation property).

**NOTE:** Typical powerful models of ML are Neural Networks, always remember that “power is nothing without control”: we need of inductive principles for the control of the complexity.

## 1.6 Learning Algorithms

A Learning Algorithms is based on data, task and model!

(Heuristic) search through the hypothesis space  $H$  ( $h \in H$ ) of the **best hypothesis** (Typically searching for the  $h$  with the minimum “error”, the best approximation to the unknown target function). Practically we want to find parameters  $w$  that give the best  $h$ .

### Example 1.2

*Learning could mean to search the best  $w$  for the linear models or best rules for symbolic model.*

$H$  may not coincide with the set of all possible functions and the search can not ”be exhaustive”: it needs to make assumptions (we will see the role of *Inductive bias*), see figure 1.7.

**Learning (terminologies):** According to the different paradigms/contexts “learning” can be differently termed or have different acceptations:

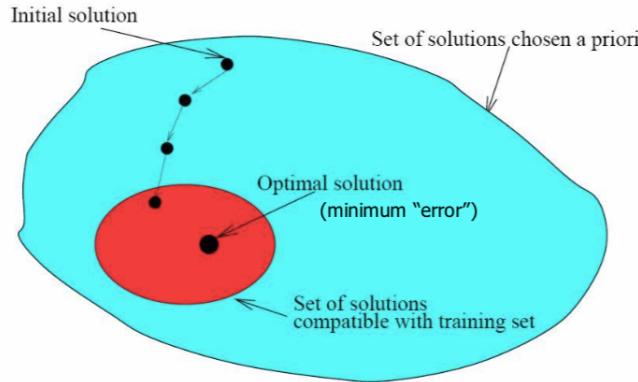


Figure 1.7: (Local) search on the hypothesis space: each point is a function, we set an initial condition and we move to a set of optimal solution (red).

- Inference (statistics)
- Inference: Abduction/Induction (logic)
- Adapting (biology, systems)
- Optimizing (mathematics)
- Training (e.g. Neural Networks)
- Function approximations (mathematics)

Can be more specifically found in other sub-fields:

- Regression analysis (statistics), curve fitting (math, CS), ...
- Or using other terminologies e.g. “Fitting a multivariate function”

## 1.7 Role of inductive bias

In order to set up a model and a learning algorithm we can make assumptions (about the nature of the target function) concerning either

**Language bias** Constraints in the model (in the hypothesis space  $H$ , due to the set of hypotheses that we can express or consider). For example we can search only on linear function.

**Search bias** Constraints or preferences in learning algorithm/search strategy. For example we could choose to search only some  $w$  for the linear search.

**Both** Search bias and inductive bias together.

Such assumptions are strictly need to obtain an useful model for the ML aims ( a model with generalization capabilities ).

We start to discuss it within examples in discrete hypotheses spaces (rules) , learning a concept (a Boolean function) [Mitchell chapt. 2]

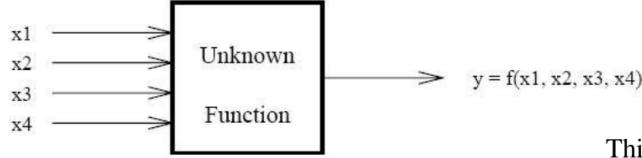
**Example 1.3** (A simple rule)

$x$  is a “cat” if  $h_{cat}(x) = 1$ , otherwise is 0 for  $x$  in “animals”

**Learning a Boolean function** Given a space of boolean variable  $x_i$  we can create a number of boolean function equal to  $2^{2^n}$ .

### Example 1.4

Given 4 boolean variable  $x_i$ ,  $i = 1, \dots, 4$  we search in the space of the combination of all possible output.



Example	$x_1$	$x_2$	$x_3$	$x_4$	$y$
1	0	0	1	0	0
2	0	1	0	0	0
3	0	0	1	1	1
4	1	0	0	1	1
5	0	1	1	0	0
6	1	1	0	0	0
7	0	1	0	1	0

This is an **ill posed** (inverse) problem:

We may violate either existence, **uniqueness**, stability of the solution or solutions

In the table there aren't all the possible combinations of the  $x_i$ , only 7 examples are given. The task is to infer the output for the other 9 combination but... There are still  $2^9$  combination of function that agree with the provided examples! ( $2^9 = 2^{16-7}$ ).

This kind of problem is ill posed so the uniqueness of solution is not guaranteed. A learner of this type is called Rote Learner.

### Definition 1.3 (Rote Learner)

A rote learner is a learning algorithm that stores examples and classify new instances only if they match with a previous observed example. If a new instance doesn't match with any of the preceding instance the rote learning just classify as "I don't know".

**Cunjunctive Rules** As second example of discrete Hypotesys Space  $H$  we could imagine to learn a discrete function with discrete inputs assuming conjunctive rules.

### Example 1.5

Take this 3 proposition:  $l_1$  = "the animal is furry",  $l_2$  = "the animal purrs",  $l_3$  = "the animal is a cat".

The conjunctive rule could be: if  $(l_1 \text{ and } l_2) = \text{True}$  then  $l_3 = \text{True}$ , else  $l_3 = \text{False}$ .

So the function  $h$  is:

$$h(l_1, l_2, l_3) = \begin{cases} l_3 & \text{if } l_1 \text{ and } l_2 \\ \text{not } l_3 & \text{otherwise} \end{cases}$$

In this space, given  $n$  proposition we can have  $3^n + 1$  semantically distinct Hypoteses (conjunctions):

- $l_i$ .
- $\text{not } l_i$ .
- Don't care.

We add the  $+1$  because all the  $h$  like  $(l_i \text{ and not } l_i)$  are equivalent to false.

### 1.7.1 Unbiased Learner

**Definition 1.4** (Consistent Hypothesis)

An hypothesis is consistent with the training set TR if  $h(\mathbf{x}) = d(\mathbf{x})$  for each training sample  $\langle \mathbf{x}, d(\mathbf{x}) \rangle$ .

**Definition 1.5** (Version Space)

The version space  $VS_{H,TR}$  is the subset of Hypotheses (respect to the Hypothesis space  $H$ ) consistent with all the training sample of the training set TR.

The version space can be found by clever algorithm described in the book (Mitchell chap. 2).

Using only the conjunctive assumption, like in the previous example, may be too restrictive: if the target concept (or function) is not in  $H$  it cannot be represented in  $H$ .

**Example 1.6** (outside target)

If  $(x_1 = 1 \text{ or } x_2 = 1)$  then  $h(\mathbf{x}) = 1$  else  $h(\mathbf{x}) = 0$ .

With this Hypothesis space we cannot represent  $x_i = 0$ .

In order to handle this problem we can choose  $H$  that express every teachable concept (among proposition). In the conjunctive rules we could choose:

$$H = \text{disjunctions, conjunctions, Negations.}$$

In this way  $H$  will surely contains the target concept: in this case  $H$  will be an **Unbiased Learner**.

### 1.7.2 Is an unbiased learner good for Generalization?

The only example that are unambiguously classified by an unbiased learner (represented with the VS) is are the training examples themselves.

**Theorem 1.2** (About unbiased learner)

An unbiased learner is unable to Generalize (on new instances).

*Proof.* Each unobserved instance will be classified positive by precisely half the hypothesis in VS and negative by the other half ( rejection: no answer is made by the VS for new input instances).

Indeed, given  $x_i$  in the test set:

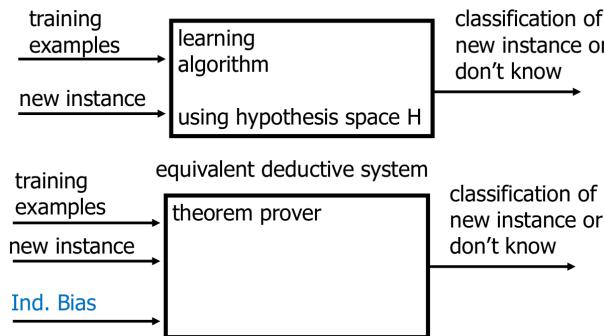
$\forall h \text{ consistent with } x_i \exists h' \text{ identical to } h \text{ except } h'(x_i) \neq h(x_i), h' \in VS \text{ and } h \in VS$ . □

So a learner that makes no prior assumptions regarding the identity of the target function/concept has no rational basis for classifying any unseen instances.

**Important:** bias is not only assumed for efficiency but it is **needed** for the generalization capability.

### 1.7.3 Inductive or Deductive System

Inductive systems are equivalent to deductive systems if we insert in our hypothesis the inductive bias. In this way the problem about the classification of new instance makes sense: doing ML we are not inventing crazy useless functions.



#### 1.7.4 Language or Search bias?

In ML is typically used a flexible approaches (expressive hypothesis spaces, universal capability of the models, e.g. Neural Networks, DT).

Usually we avoid the language bias, hence without excluding a priori the unknown target function. We retain an inductive bias but focusing on the search bias (which is ruled by the learning algorithm).

In practice we will use an incomplete search strategy.

#### Conclusions:

- Learning without bias cannot extract any regularities from data (lookup-table: no generalization capabilities).
- Every state-of-the-art ML approach shows an inductive bias.
- Issue: characterize the bias for different models/learning approaches... Is an Inductive Bias better than another?

### 1.8 Task + Model = Loss

We have to find a “good” approximation to  $f$  from examples. How to measure the quality of the approximation?

We want to measure the “distance” between  $h(x)$  (output of the model for input  $\mathbf{x}$ ) and  $d$ .

*Minimization of errors in training, check of errors in test*

We will use:

- *Loss function*:  $L(h(\mathbf{x}), d)$  (high value means poor approximation)
- The Error (or Risk) is an expected value of the loss:

$$\text{Empirical Risk} : R_{emp} = \frac{1}{l} \sum_{i=1}^l L(h(\mathbf{x}_i), d_i).$$

e.g. a “sum” or mean of the loss over the set of samples.

We will change the loss function  $L$  for different tasks.

#### Common Tasks review

A possible classifications of common learning tasks specifying the (changing of the) nature of the loss function, output and hypothesis space.

- Survey of common learning tasks
- Nature of models (hypothesis spaces) for different class of tasks.

#### 1.8.1 Loss Function example: Regression

In a regression task we want to predict a numerical value. We have an **Hypothesis Space  $H$**  that is a set of real-valued functions and the **Loss function** will measures the approximation accuracy/error between  $h(x_i)$  and  $d_i = f(x_i) + e$  (real value function + random error).

A common loss function for Regression (predicting a numerical value) is the *squared error*:

$$L(h(\mathbf{x}_i), d_i) = (d_i - h(\mathbf{x}_i))^2.$$

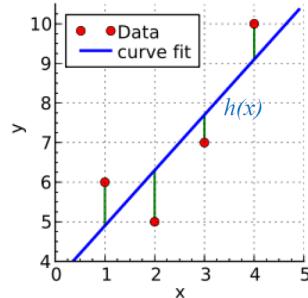
We use that error because we want the distance and a negative or positive value makes no different).

$R_{emp}$ : the mean over the data set provide the *Mean Square Error* (MSE)

In the example we have  
 $h(x) = w_1x + w_0$  as the blue line  
and in green the errors at the **data points**  $(x_i, y_i)$  (in red), where the target  $d_i$  for  $x_i$  is  $y_i$  in the example

*The Mean Square Error (MSE)*  
is the mean of the square of the green errors.

$$E(w) = \frac{1}{l} \sum_{p=1}^l (y_p - h_w(x_p))^2$$



Note: this plot is taken from internet, I used different colors before: blue for the points (data) and red for the line in my previous plot.  
Also the y are the desired (target d) values

### 1.8.2 Loss Function example: Classification

Classification of data into discrete classes,  $d_i$  can be e.g. 0/1 and  $h(x_i)$  will predict 0/1. So our **Loss Function** will measure the classification error:

$$L(h(\mathbf{x}_i), d_i) = \begin{cases} 0 & \text{if } h(\mathbf{x}_i) = d_i \\ 1 & \text{otherwise} \end{cases}$$

$R_{emp}$ : The mean over the data set provide the number/percentage of misclassified patterns

#### Example 1.7

20 out of 100 are misclassified  $\rightarrow$  20% errors, i.e. 80% of accuracy

### 1.8.3 Loss Function example: Clustering and Vector Quantization

**Goal:** optimal partitioning of unknown distribution in x-space into regions (clusters) approximated by a cluster center or prototype. e.g. see figure 1.2

**H:** a set of vector quantizers  $x \rightarrow c(x)$  (continuous space  $\rightarrow$  discrete space)

**Loss Function:** would be the squared error distortion:

$$L(h(\mathbf{x}_i)) = \langle (\mathbf{x}_i - h(\mathbf{x}_i)), (\mathbf{x}_i - h(\mathbf{x}_i)) \rangle \quad (\text{inner product})$$

Proximity of the pattern to the centroid of its cluster

### 1.8.4 Loss Function example: Density estimation

Density estimation (generative, “parametric methods”) from an assumed class of density

- **Output:** a density e.g. normal distribution with mean  $m$  and variance  $\text{sigma}^2 : p(x | m, \text{sigma}^2)$
- **H:** a set of densities (e.g.  $m$  and  $\text{sigma}^2$  are the two unknown parameters)
- A common **loss function** for density estimation:

$$L(h(\mathbf{x}_i)) = -\ln(h(\mathbf{x}_i)) \longrightarrow \text{We'll see later}$$

- Related to "maximizing the (log) likelihood function". [not hear]
- E.g.  $P(x_1, x_2, x_3, \dots | m, \text{sigma}^2)$

## 1.9 GENERALIZATION

Learning: search for a good function in a function space from known data (typically minimizing an Error/Loss), but how we can say that this model is good for our task after the learning step?

**Note:** This is the answer for the question: "What's the meaning of Machine Learning?"

A model is Good with respect to the **generalization error**: how accurately the model predicts over novel samples of data (Error/Loss measured over new data)

So *Generalization* is a crucial point of ML. We will see the difference between "Easy to use ML tools" and the "correct/good use of ML".

So we have two main phases:

- **Learning phase (training, fitting):** build the model from known data – *training data* (and bias).
- **Predictive phase (test):** apply to new example (we take the input  $\mathbf{x}$  and we compute the response by the model): evaluation of the predictive hypothesis, i.e. of the **generalization capability**.

The Predictive phase corresponds to the Deployment/Inference use of the ML built model.

⇒ Generalization is a crucial point of ML!!!

Evaluation of performances for ML systems = predictive accuracy  
Estimated by the error computed on the (Hold out) Test Set

Accuracy/performance estimation is a critical aspect, we can do it by:

- theory to understand under what mathematical conditions a model is able to generalize (*Statistical Learning Theory* [Vapnik]). For example: how many data is needed to generalize? It makes sense to use few data to generalize?
- Empirical (training, test) and cross-validation techniques

**NB:** The performance on training data provide an overoptimistic evaluation, so never test accuracy on training set!

A very important phase is **Validation**!

**Definition 1.6** (Inductive Learning Hypothesis)

*Any hypothesis  $h$  found to approximate the target function ( $f$ ) well over a sufficiently large set of training examples will also approximate the target function well over any other unobserved examples.*

This is the fundamental assumption of inductive learning (Supervised learning) (e.g. in concept learning) and we will have much more to say about it.

### Definition 1.7 (Overfitting)

A model is in overfitting if it outputs an hypothesis  $h(\cdot) \in H$  having true/generalization error (risk)  $\epsilon$  and empirical (training) error  $E$ , but There is another  $h'(\cdot) \in H$  having  $E' > E$  and  $\epsilon' < \epsilon$ .

Remember that we are interested in **generalization capability**, not in **fit capability**, the first one is given by generalization error  $\epsilon$  and the second by the training error  $E$ .

#### 1.9.1 Complexity on case of study

Let's take an example with a **parametric model** for regression: **Polynomial Curve Fitting Example**. We consider just one variable  $x$  and we assume to know the target function  $h_w(x)$  (see figure 1.8a), as error function we will use the Sum-of-Squares Error (see figure 1.8b).

- The set of function is assumed as polynomials with degree  $M$
- The complexity of the hypothesis increase with the degree  $M$
- $l =$  number of examples

The Hypothesis Space in this case is:

$$h_w(x) = \sum_{j=0}^M w_j x^j.$$

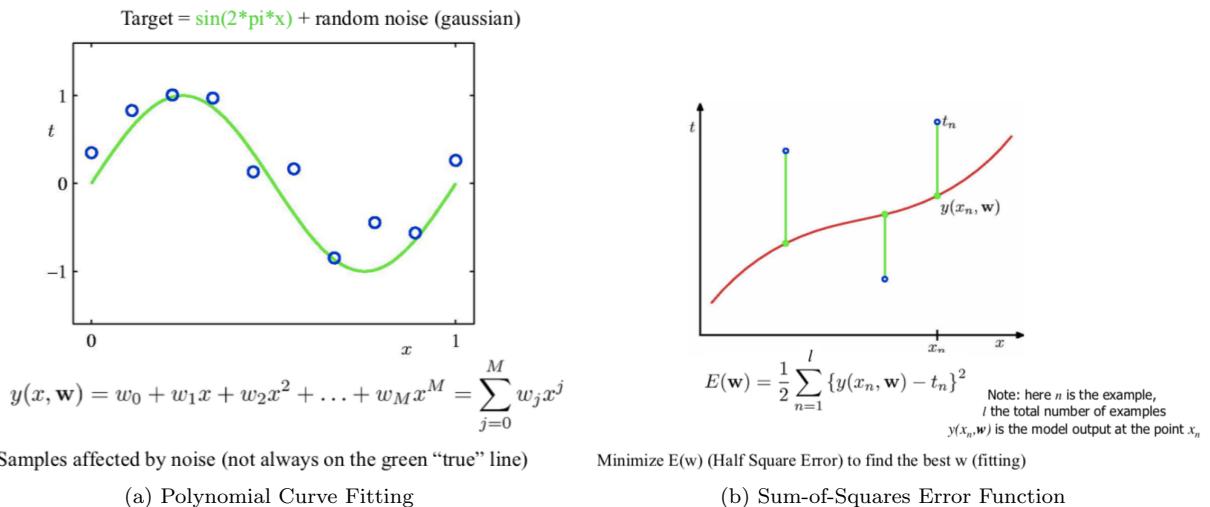


Figure 1.8: A simple parametric model for regression example

**Warning:** This is an artificial simplified task (unrealistic due to the use of just 1 input variable, the fact that we know the target function in advance, ...).

Let's analyze how good is a model if we increase the complexity and how change if the number of data, made available in the training phase, increases.

**Case  $l = 10$ :**

Assume that we have some few data (figure 1.8a) and let's see how our model will fit the data if we increase the complexity of the model.

Let's see some cases:

- $M = 0$ : in this case we are in **underfitting**, we have a very simple model that cannot fit the data. With  $M = 0$  the model it's just the mean. See figure 1.9a.
- $M = 1$ : Linear model, still an underfitting model, doesn't fit good the data. See figure 1.9b.

- $M = 3$ , this time, the model seems very good, we have a low error. See figure 1.9c.
- $M = 9$ : Too complex model, it's fit the noise too!, the error on the training test is  $E(w) = 0$ , but error on the test set? See figure 1.9d. Poor representation of the (green) true function due to **overfitting**.

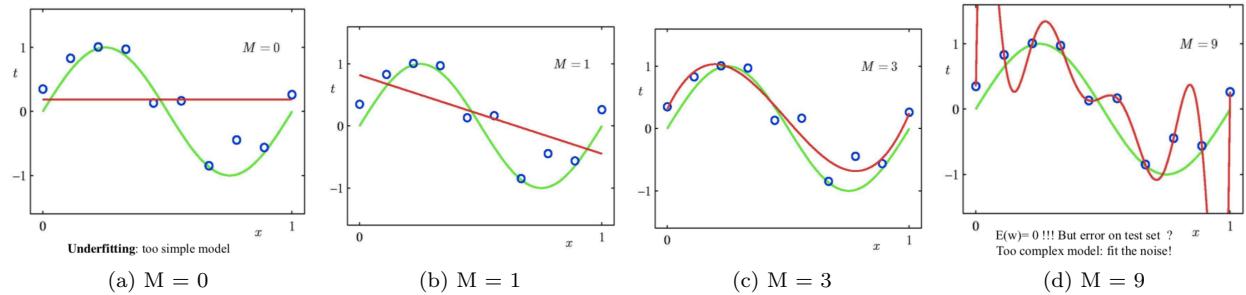


Figure 1.9: The complexity of the hypothesis increase with the degree  $M$

So let's plot Root-Mean-Square(RMS) Error and see how change with the complexity ( $M$ ) of the model, where  $w^*$  are the polynomial coefficients:

$$E_{RMS} = \sqrt{2E(w^*)/l}$$

As we can see in figure 1.10 the error is 0 in the training test (overfitting) but the error is really high on the test set. the model is not able to generalize.

Our aim is to stay in the middle of the plot in figure 1.10.

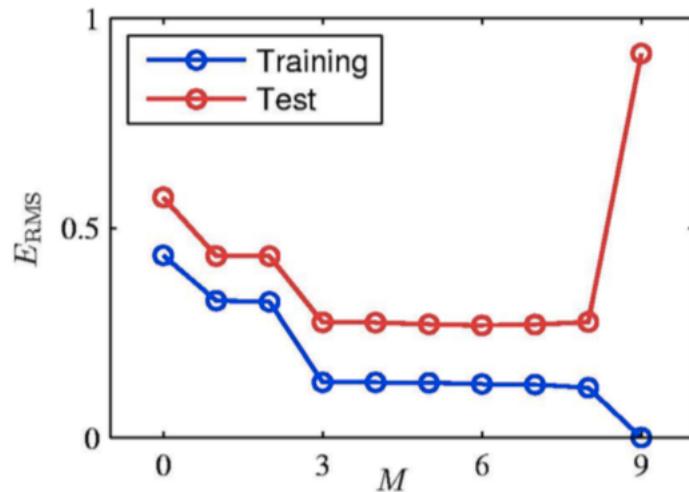


Figure 1.10: Mean Square Error for different values of  $M$  on the test set (red) and on training set (blue).

	$M = 0$	$M = 1$	$M = 3$	$M = 9$
$w_0^*$	0.19	0.82	0.31	0.35
$w_1^*$		-1.27	7.99	232.37
$w_2^*$			-25.43	-5321.83
$w_3^*$			17.37	48568.31
$w_4^*$				-231639.30
$w_5^*$				640042.26
$w_6^*$				-1061800.52
$w_7^*$				1042400.18
$w_8^*$				-557682.99
$w_9^*$				125201.43

Figure 1.11: ...

**Case  $l = 15$ :**

With a 9th order polynomial model ( $M = 9$ ) and more data the model seems to get a better generalize for the future data, but still not good. See figure 1.12a.

**Case  $l = 100$ :**

With a 9th order polynomial model ( $M = 9$ ) and more data the model seems to get a better generalize for the future data, but still not good. See figure 1.12b.

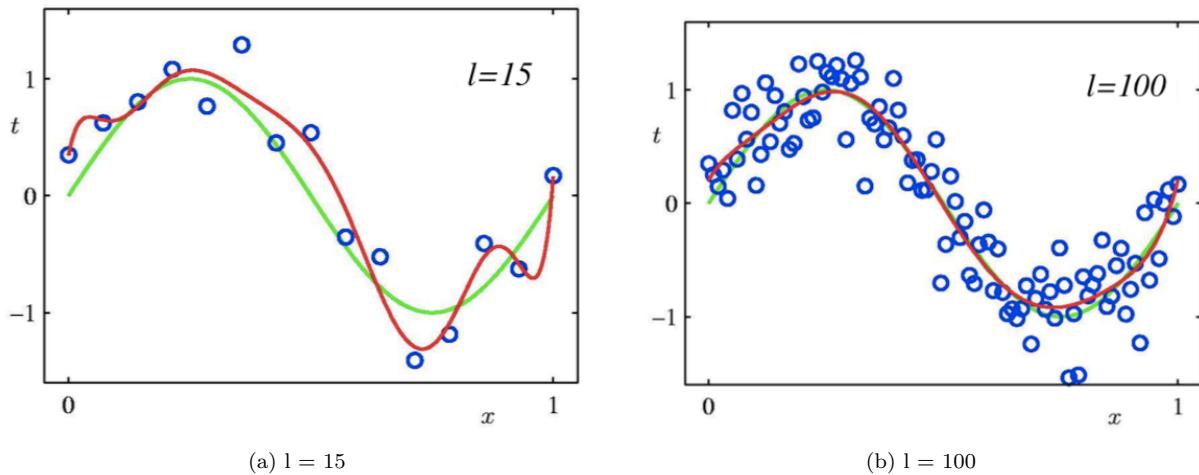


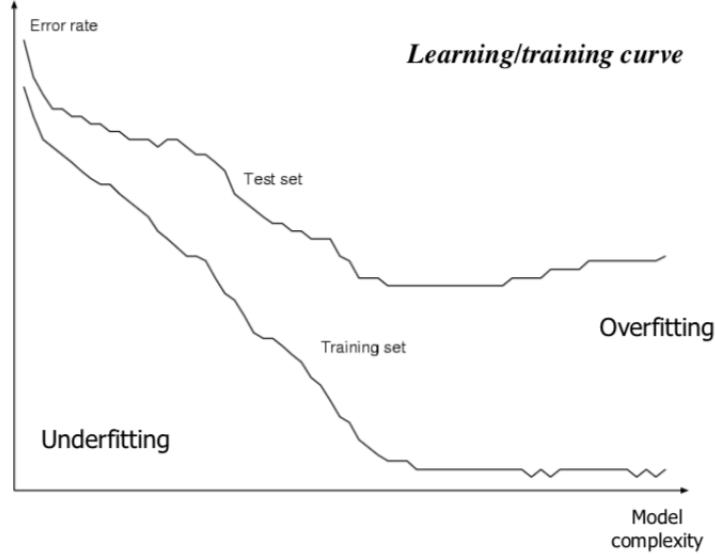
Figure 1.12: The complexity of the hypothesis with the degree 9 when the number of data change

So model complexity and the number of data are very important for the generalization capability of a model, let's put all together:

- The generalization capability (measured as a risk or test error) of a model with respect to the training error and avoid overfitting and underfitting zones

- The role of model complexity
- The role of the number of data

## Typical behavior of learning



### 1.9.2 Toward Statistical Learning Theory (SLT)

Riassumming the previous section our goals are:

- To investigate on *generalization capability* of a model (measured as a risk or test error):
  - with respect to the train error
  - with respect to the overfitting and underfitting zone.

We are also interested in the role of the model complexity and the role of the number of data.

Statistical Learning Theory (SLT) is a general theory relating such topics. In a (Simplified) Formal Setting:

1. we want to approximate an unknown function  $f(\mathbf{x})$
2. minimize a risk function:

$$R = \int L(d, h(\mathbf{x})) dP(\mathbf{x}, d)$$

This is the **True error** over all the data (that we don't have).  $d$  is the value from the teacher and  $P(x, d)$  the probability distribution of the data. A loss (or cost) function could be for example:  $L(h(\mathbf{x}), d) = (d - h(\mathbf{x}))^2$ .

Note that we typically don't have  $P\dots$

3. then search  $h$  in  $H$  minimizing  $R$

But we have only a finite data set:  $TR = (\mathbf{x}_i, d_i) \forall i = 1, \dots, l$ . So we can't use  $R$  as minimize risk function. To search  $h$ , we will minimize the empirical risk (training error), finding the best values for the model free parameters:

$$R_{emp} = \frac{1}{l} \sum_{i=1}^l (d_i - h(\mathbf{x}_i))^2.$$

This is the Empirical Risk Minimization (ERM) (our *Inductive Principle*).

## Vapnik-Chervonenkis-dim and SLT: a general theory

We can use  $R_{emp}$  to approximate  $R$ !

### Definition 1.8 (VC-dim)

*Measure complexity of  $H$  (flexibility to fit data), e.g. Num. of parameters for polynomials, NN, ...*

The Vapnik-Chervonenkis bound (VC-bound(s)) is in the form:

$$R \leq R_{emp} + \epsilon(1/l, VC, 1/\delta)$$

This equation holds with probability  $1 - \delta$ . We can choose  $\delta$  (from the point of machine learning this is not so important).

**Important** For our point of view the important parameters are  $l$ : the number of data and VC-dim (like the number of parameters in the model).

where  $R_{emp} + \epsilon$  is the **guaranteed risk** and  $\epsilon$  is the **VC-confidence**

- $\epsilon$  is a function that grows with VC-dim and decrease with  $l$  (number of data) and  $\delta$ .
- Higher  $l$  (data): lower  $R$
- Higher VC-dim (fix  $l$ ) : lower  $R_{emp}$  but  $R$  may increase (overfitting)

Over/under fitting with this...?

**Structural Risk Minimization: find a trade-off** Concept of control of the model complexity (flexibility): trade-off between model complexity and TR (training) accuracy (fitting).

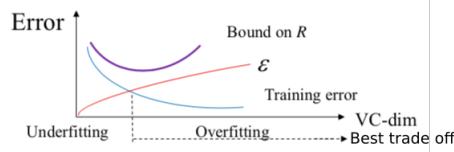


Figure 1.13: Blu+Red=purple, in the figure  $l$  is fixed. The purple is the bound of  $R$  and not the real  $R$  because of the  $\leq$ .

### Definition 1.9 (Model selection)

*The model selection consist in choise of the model ( $H$ ) with the better bound on the true risk.*

### Example 1.8

*It is possible to derive an upper bound of the ideal error which is valid with probability  $(1 - \delta)$ , delta being arbitrarily small, of the form:*

- General:  $R \leq R_{emp} + \epsilon(1/l, VC, 1/\delta)$
- Example:  $R \leq R_{emp} + \epsilon(VC/l, -\ln(\delta/l))$
- There are different bounds formulations according to different classes of  $f$ , of tasks, etc.
- More in general, in other words (simplifying): we can make a good approximation of  $f$  from examples, provided we have a good number of data, and the complexity of the model is suitable for the task at hand.

### 1.9.3 Complexity control

SLT - Statistical Learning Theory:

- It allows formal framing of the problem of generalization and overfitting, providing analytic upper-bound to the risk  $R$  for the prediction over all the data, regardless to the type of learning algorithm or details of the model..
- The ML is well founded: the Learning risk can be analytically limited and only few concepts are fundamentals !
- SLT has allowed to leads to new models (e.g SVM) and other methods that directly consider the control of the complexity in the construction of the model
- bases one of the inductive principles on the control of the complexity
- explain the main difference with respect to supporting methods from CM (providing the techniques to perform fitting), apart from modelling aspects

But there are other open questions: what (other) principles are to found the control of the complexity? How to work in practice? How to measure the complexity (or fitting flexibility)? How find the best trade-off between fitting and model complexity?

## 1.10 VALIDATION

Evaluate generalization capabilities (of your  $h(x)$ ). **Warning:** The performance on training data provide an overoptimistic evaluation (we have seen "overfitting").

Evaluation of performances for ML systems = Predictive accuracy

Validation phase has two main aims:

- **Model selection:** estimating the performance (generalization error) of different learning models in order to choose the best one (to generalize).  
this includes search the best hyper-parameters of your model (e.g. polynomial order, ...).

It returns a model

- **Model assessment:** having chosen a final model, estimating/evaluating its prediction error/ risk (generalization error) on new test data (measure of the quality/performance of the ultimately chosen model).

It returns an estimation

**Gold rule:** Keep separation between goals and use separate data sets for this two operation.

In an ideal world, for validation we should have:

- a large training set (to find the best hypothesis, see the theory)
- a large validation set for model selection
- a very large external unseen data test set

But with a finite and often small data set we will have just a estimation of the generalization performance. Let's see two basic techniques for validation: Simple hold-out (basic setting) and K-fold Cross Validation.

### 1.10.1 Hold out cross validation

Hold out: basic setting.

Partition data set D into training set (TR), validation or selection set (VL) and test set (TS). See figure 1.14

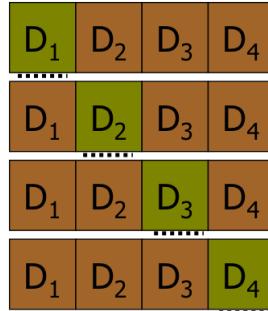


Figure 1.15: k-fold cross validation

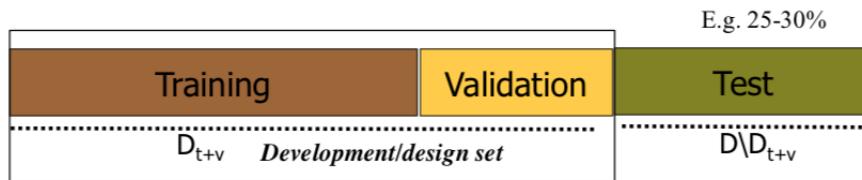


Figure 1.14: Hold out cross validation

- All the three sets are disjoint sets
- Training is used to run the training algorithm
- VL can be used to select the best model (e.g hyper-parameters tuning)
- Test set is not to be used for tuning/selecting the best  $h$ : it is only for model assessment

**Don't touch the test set!** If you "come back" to training after testing on TS you are cheating! That's not machine learning...

### 1.10.2 Hold out and K-fold cross validation

When we have a small number of data, Hold out Cross Validation can make insufficient use of data. To solve this problem we can use another technique called: **K-fold Cross-Validation**:

- Split the data set  $D$  into  $k$  mutually exclusive subsets  $D_1, D_2, \dots, D_k$
- Train the learning algorithm on  $\frac{D}{D_i}$  and test it on  $D_i$  repeat this phase  $k$  time and then we take the mean of the validation results.
- Can be applied for both VL or TS splitting
- It uses all the data for training and validation/testing

But this technique has some issues:

- How many folds? 3-fold, 5-fold , 10-fold, ...., 1-leave-out
- Often computationally very expensive (we have to perform training and validation phases  $k$  times)

Combinable with validation set, double-K-fold CV, ....

### 1.10.3 TR/VL/TS by a schema

:

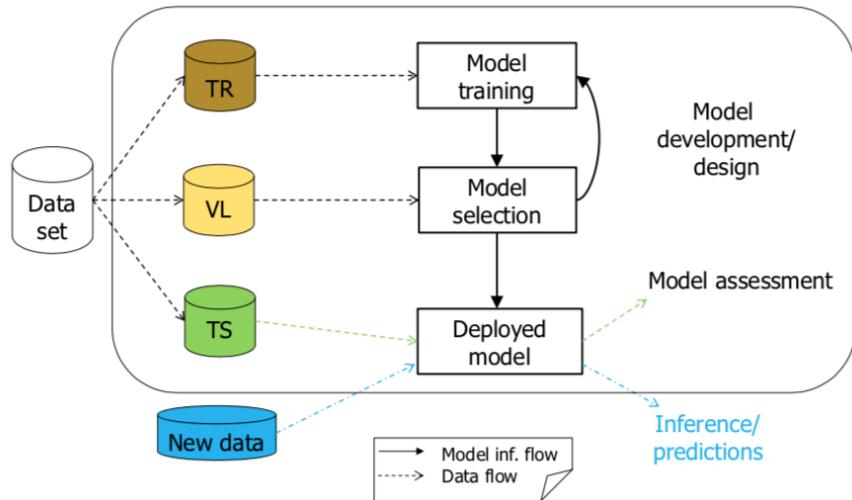


Figure 1.16: TR/VL/TS by a schema

#### 1.10.4 Classification Accuracy

In the field of machine learning and specifically the problem of statistical classification, a confusion matrix, also known as an error matrix. A confusion matrix is a table that is often used to describe the performance of a classification model (or “classifier”) on a set of test data for which the true values are known. It allows the visualization of the performance of an algorithm. See figure 1.17.

Predicted \ Actual	Positive	Negative
Positive	TP	FN
Negative	FP	TN

Figure 1.17: Confusion matrix

The number of correct and incorrect predictions are summarized with count values and broken down by each class. This is the key to the confusion matrix. The confusion matrix shows the ways in which your classification model is confused when it makes predictions. It gives us insight not only into the errors being made by a classifier but more importantly the types of errors that are being made.

Definition of the Terms:

- Positive (P) : Observation is positive (for example: is an apple).
- Negative (N) : Observation is not positive (for example: is not an apple).
- True Positive (TP) : Observation is positive, and is predicted to be positive.
- False Negative (FN) : Observation is positive, but is predicted negative.
- True Negative (TN) : Observation is negative, and is predicted to be negative.
- False Positive (FP) : Observation is negative, but is predicted positive.

**Classification Rate/Accuracy** is given by the relation:

$$\frac{TP + TN}{Total} = \frac{TP + TN}{TP + TN + FP + FN}$$

Accuracy is not a good score for unbalanced dataset.

**NOTE:** for binary classif.: 50% correctly classified = “coin” (random guess) predictor. Of course could exists trivial classifier with unbalanced data (e.g. 99% of the data are positive).

Two importat statistical measures are: *Specificity* and *Sensitivity*.

### Specificity

Specificity (also called the true negative rate) measures the proportion of actual negatives that are correctly identified as such (e.g., the percentage of healthy people who are correctly identified as not having the condition).

$$\text{Specificity} = \frac{TN}{FP + TN} = 1 - FPR$$

where FPR (fall-out or false positive rate) =  $FP/N = FP/(FP + TN)$ .

### Sensitivity

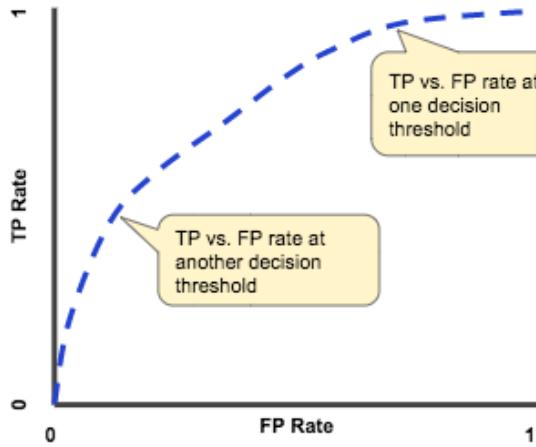
Sensitivity (also called the true positive rate, the recall, or probability of detection[1] in some fields) measures the proportion of actual positives that are correctly identified as such (e.g., the percentage of sick people who are correctly identified as having the condition).

$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

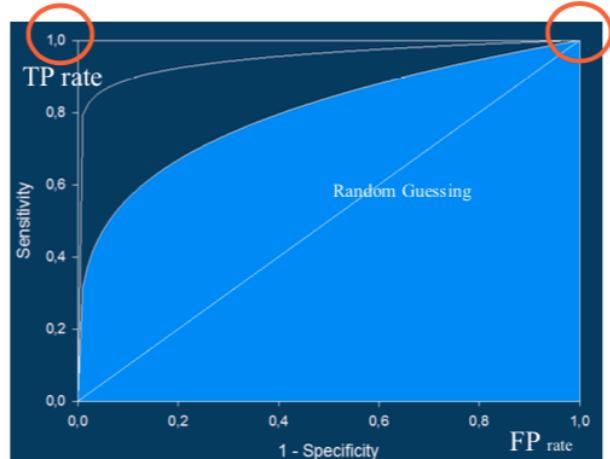
### ROC Curve

An ROC curve (receiver operating characteristic curve) is a graph showing the performance of a classification model at all classification thresholds. This curve plots two parameters: Sensitivity (True Positive Rate (TPR)) and False Positive Rate (FPR) (1 - Specificity).

Lowering the classification threshold classifies more items as positive, thus increasing both False Positives and True Positives. See figure 1.18a.



(a) AUC (Area under the ROC Curve)



(b) AUC

Figure 1.18: ROC curve

**AUC** stands for ”Area under the ROC Curve.” and measures the entire two-dimensional area underneath the entire ROC curve (think integral calculus) from (0,0) to (1,1). See figure 1.18b.

AUC provides an aggregate measure of performance across all possible classification thresholds. One way of interpreting AUC is as the probability that the model ranks a random positive example more highly than a random negative example.

The diagonal corresponds to the worst classifier (random guessing). Better curves have higher AUC (Area Under the Curve). In 1.0 we have the perfect classification.

## 1.11 The Design Cycle

**Data collection:** adequately large and representative set of examples for training and test the system

**Data representation:** Often the most critical phase for an overall success.

- domain dependent, exploit prior knowledge of the application expert
- Feature selection
- Outliers detection
- Other preprocessing: variable scaling, missing data,..

**Model choice:**

- Statement of the problem.
- Hypothesis formulation: You must know the limits of applicability of your model.
- Complexity control.

**Building of the model (core of ML):** through the learning algorithm using the training data.

**Evaluation:** performance = predictive accuracy.

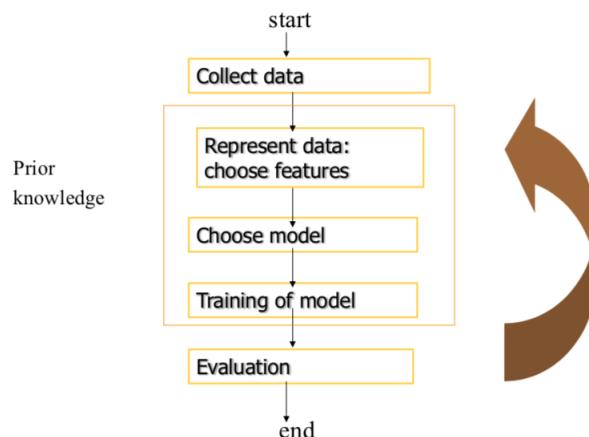


Figure 1.19: Design cycle

## 1.12 Misinterpretations

For every statistical models (including Data Mining (DM) applications):

- Causality is (often) assumed and a set of data representative of the phenomena is needed.
  - Not for unrelated variables and for random phenomena (lotteries)
  - Uninformative input variables → poor modeling → Poor learning results
- Causality cannot be inferred from data analysis alone:
  - People in Florida are older(on av.) than in other US states.

- Florida climate causes people to live longer ?
- May be there is a statistical dependencies for reasons outside the data.
- More specifically for ML:
  - Powerful models (even for “garbage” data) → higher risk !
  - Not-well validated results: the predicted outcome and the interpretation can be misleading.

## 2 Linear models

In this section we will going to analyze a linear model for classification and regression (Supervised Learning) both as task in function approximation.

This is a **Parametric model**: A learning model that summarizes data with a set of parameters of fixed size (independent of the number of training examples) is called a parametric model.

- **Given:** Training examples as  $\langle \text{input}, \text{output} \rangle = \langle x, d \rangle$ , we have labeled examples for some for some unknown function  $f$ . (For us  $f$  is known only at the given example points).
- **Find:** a good approximation to  $f$  (that can used for prediction on unseen data  $x'$

The target value  $d$  (or  $t$  or  $y$ ), given by the teacher according to  $f(x)$ , are numerical/ categorical label:

- Classification:  $f(x)$  return the (assumed) correct class for  $x$ , where  $f(x)$  is a discrete valued function.
- Regression: approximate a real-valued target function (in  $\mathbb{R}$  o  $\mathbb{R}^K$ ).

Here some Data notation in figure 2.1:

Pattern	$x_1$	$x_2$	$x_j$	$x_n$
Pat 1	$x_{1,1}$	$x_{1,2}$		$x_{1,n}$
...				
Pat $p$	$x_{p,1}$	$x_{p,2}$	$x_{p,j}$	$x_{p,n}$
...				

**$X$**  is a matrix  $I \times n$   
 $I$  rows,  $n$  columns  
 $p=1..I, j=1..n$

We often need to omit some index when the context is clear, e.g.:

- Each row, generic  **$x$**  (vector - bold), a raw in the table: example, pattern, instance, sample,....
- $x_i$  or  $x_j$  (scalar): component  $i$  or  $j$  (given a pattern, i.e. omitting  $p$ )
- $x_p$  or  $x_i$  (vector - bold)  $p$ -th or  $i$ -th raw in the table = pattern  $p$  or  $i$
- $x_{pj}$  (scalar) also as **( $x_p$ )**: component  $j$  of the pattern  $p$
- For the target  **$y$**  we will typically use just  $y_p$  with  $p=1..I$

Figure 2.1: Data notation for this section

Now will we start to see linear models for Regression and classification where the  $H$  (hypothesis space is linear). Same model can be applied for both tasks and we will see how.

*"Despite the great inroads made by modern nonparametric regression techniques, linear models remain important, and so we need to understand them well."* (Hastie)

The linear model has been the mainstay of statistics and has a lot of studies and in many books (mathematics, statistics, numerical analysis, applicative fields, ML, ...). This model is also used/included in more complex models.

We will start with the simplest form: linear in the input variables.

### 2.1 Regression

Let's see first how we can formulate the learning problem as a **Least mean square (LMS)** problem and let's start to see it in a simplified setting: **univariate case**.

A regression task is the process of estimating of a real-value function on the basis of finite set of noisy samples, we have known pairs  $(x, f(x) + \text{random noise})$  and we want to find an  $h$  (hypothesis) that fit the data. See figure 2.2.

We want to solve it (how to find  $w$ ) in a systematic way.

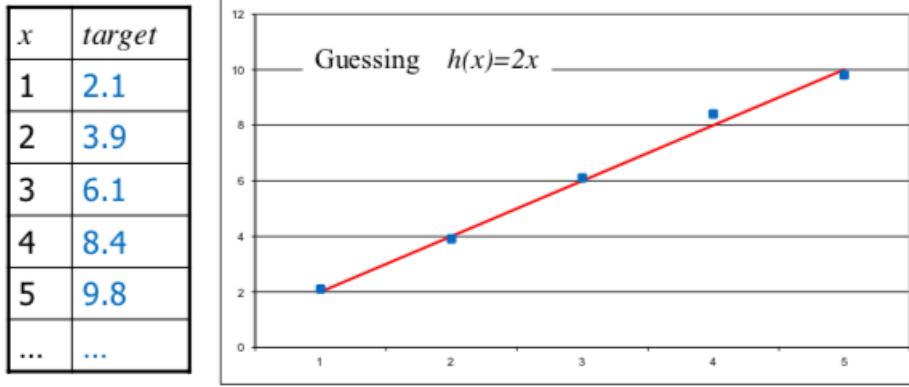


Figure 2.2: Regression Example

### 2.1.1 Univariate Linear Regression

Univariate case, simple linear regression:

- we start with 1 input variable  $x$  and 1 output variable  $y$
- we assume a model  $h_w(x)$  expressed as:

$$h_w(x) = \text{out} = w_1x + w_0$$

where  $w$  are real-valued **coefficients/free parameters (weights)**.

The idea is **fitting** the data by a “straight line”.

In this case we have Infinite hypothesis space (continuous  $w$  values) but we have nice solution from classical math (going back to Gauss/Legendre 1795!).

Surprisingly we can “learn” by this basic tool and although simple it include many relevant concept of modern ML and it is a basis of evolved methods in the field.

⇒ **Learning via LMS:**

**Learn:** means find the  $w$  such that minimize error/empirical loss (best data fitting – on the training set with  $l$  examples).

- Given a set of  $l$  training example  $(x_p, y_p)$
- find  $h_w(x)$  in the form:  $w_1x + w_0$  (hence the values of  $w$ ) that minimizes the expected loss on the training data.

As Loss function we will use the square of errors, Least (Mean) Square: find  $w$  to minimize the residual sum of squares:  $\operatorname{argmin}_w \|Error(\mathbf{w})\|$

$$\begin{aligned} Loss(h_{\mathbf{w}}) &= E(\mathbf{w}) = \sum_{p=1}^l (y_p - h_{\mathbf{w}}(x_p))^2 = \\ &= \sum_{p=1}^l (y_p - (w_1x_p + w_0))^2. \end{aligned}$$

Where  $x_p$  is p-th input/pattern/example,  $y_p$  the output for  $p$ ,  $w$  free par.,  $l$  num. of examples.

**Note:**

- to have the mean, divide by  $l$

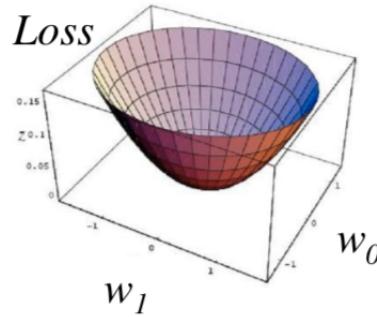
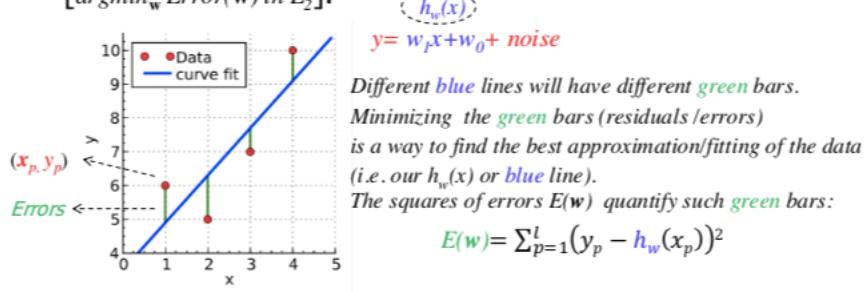


Figure 2.3: Loss function plot with two free parameters

- On the notation: Indeed for the univariate case, with 1 variable:  $x_p = x_{p,l} = (x_p)_l$

The method of least squares is a standard approach to the approximate solution of over-determined systems, i.e., sets of equations in which there are more equations than unknowns.

- **Least (Mean) Square:** Find  $w$  to *minimize* the residual sum of squares  
[ $\operatorname{argmin}_w \text{Error}(w)$  in  $L_2$ ]:



**Note:** Why the mean square error with the  $L_2$  norm? Because is a differentiable function that gives always positive values.

⇒ **How to solve?:**

Remember: local minimum as stationary point: the gradient is null:

$$\frac{\partial E(\mathbf{w})}{\partial w_i} = 0, \quad i = 1, \dots, \dim_{\text{input}} + 1 = 1, \dots, n + 1$$

For the simple Lin. Regr. (2 free parameters):

$$\frac{\partial E(\mathbf{w})}{\partial w_i} = 0 \quad \frac{\partial E(\mathbf{w}_0)}{\partial w_0} = 0$$

We have a convex loss function, so there is no local minima and there is a closed form. The solution is:

$$w_l = \frac{\sum x_p y_p - \frac{1}{l} \sum x_p \sum y_p}{\sum x_p^2 - \frac{1}{l} (\sum x_p)^2} = \frac{\text{Cov}[x, y]}{\text{Var}[x]}, \quad w_0 = \bar{y} - w_l \bar{x}$$

$$\frac{1}{l} \sum_{p>l} y_p \quad \frac{1}{l} \sum_{p>l} x_p$$

It isn't mandatory to memorize this formula **but** for exercise try to reproduce the math to arrive there...

Let's compute the gradient for 1 (each) pattern p:

$$\begin{aligned}\frac{\partial E(\mathbf{w})}{\partial w_i} &= \frac{\partial(y - h_{\mathbf{w}}(x))^2}{\partial w_i} = 2(y - h_{\mathbf{w}}(x)) \frac{\partial(y - h_{\mathbf{w}}(x))}{\partial w_i} = \\ &= 2(y - h_{\mathbf{w}(x)})) \frac{\partial(y - (w_1x + w_0))}{\partial w_i}\end{aligned}$$

and we will have:

$$\frac{\partial E(\mathbf{w})}{\partial w_0} = -2(y - h_{\mathbf{w}}(x)) \quad ; \quad \frac{\partial E(\mathbf{w})}{\partial w_1} = -2(y - h_{\mathbf{w}}(x))x.$$

then we will sum up for l patterns  $(x_p, y_p)$ :

$$\frac{\partial E(\mathbf{w})}{\partial w_0} = -2 \sum_{p=1}^l (y_p - h_{\mathbf{w}}(x_p)) \quad ; \quad \frac{\partial E(\mathbf{w})}{\partial w_1} = -2 \sum_{p=1}^l (y_p - h_{\mathbf{w}}(x_p))x_p.$$

### 2.1.2 Linear Regression with multidimensional inputs case

Assuming column vector  $\mathbf{x}, \mathbf{w} \in \mathbb{R}^n$ , number of data  $l$ :

$$\mathbf{w}^T \mathbf{x} + w_0 = w_0 + w_1x_1 + w_2x_2 + \dots + w_nx_n = w_0 + \sum_{i=1}^n w_i x_i$$

Note:

- that often (in NN), as before, the transpose notation T in  $w^T$  is omitted
- $w_0$  is the intercept/threshold/bias/offset (has nothing to do with the inductive bias, bias is just a name here)

Often it is convenient to include the constant  $x_0 = 1$  so that we can write:

$$\mathbf{w}^T \mathbf{x} = \mathbf{x}^T \mathbf{w}, \quad \mathbf{x}^T = [1, x_1, x_2, \dots, x_n] \text{ and } \mathbf{w}^T = [w_0, w_1, w_2, \dots, w_n]$$

So, the “linear” model is now:

$$h(\mathbf{x}_p) = \mathbf{x}_p^T \mathbf{w} = \sum_{i=0}^n x_{p,i} w_i, \quad w_i \text{ continuous (free) parameters “weights”}$$

## 2.2 Classification

We want now to use the same linear model (with LMS) presented for the regression task and use it for the classification task. The problem in Classification is shown in figure 2.4

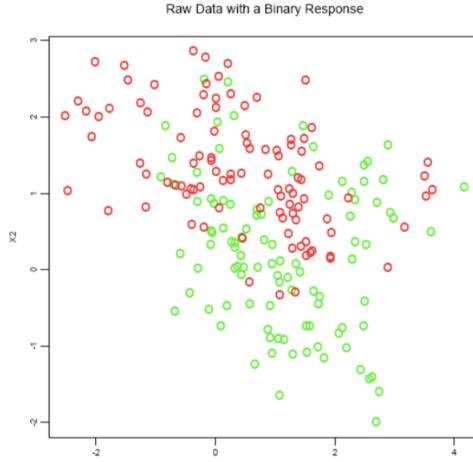


Figure 2.4: A classification problem (Data may be generated by gaussian distribution (for each class) with different means or by a mixture of different low variance gaussian distributions)

We have 200 points generated in  $\mathbb{R}^2$  from an unknown distribution, 100 in each of two classes and we want to build a rule to predict the color of future points.

#### We reuse the linear model for the classification task:

The same models (used for regression) can be used for classification: categorical targets, e.g. 0/1 or  $-1/+1$

- In this case we use an hyperplane ( $\mathbf{w}\mathbf{x}$ ) assuming negative or positive values.
- We exploit such models to decide if a point  $\mathbf{x}$  belong to positive or negative zone of the hyperplane (to classify it)
- So we want to set  $\mathbf{w}$  (by learning) s.t. we get good classification accuracy

#### Geometrical view: hyperplane:

We define an hyperplane:  $\mathbf{w}^T \mathbf{x}$ , see figure 2.5 where our hyperplane is:

$$\mathbf{w}^T \mathbf{x} = w_1 x_1 + w_2 x_2 + w_0 = 0$$

#### Geometrical view: classifier:

In this case our hypothesis ( $h(x)$ ) is called **Linear threshold unit (LTU)** and is defined as follow:

$$h(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{w}\mathbf{x} + w_0 \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

or

$$h(\mathbf{x}) = \text{sign}(\mathbf{w}\mathbf{x} + w_0)$$

Linear threshold unit (LTU)

Indicator functions

In case of  $w_0$  included in  $\mathbf{w}$ :

$$h(\mathbf{x}_p) = \text{sign}(\mathbf{x}_p^T \mathbf{w}) = \text{sign}\left(\sum_{i=0}^n x_{p,i} w_i\right)$$

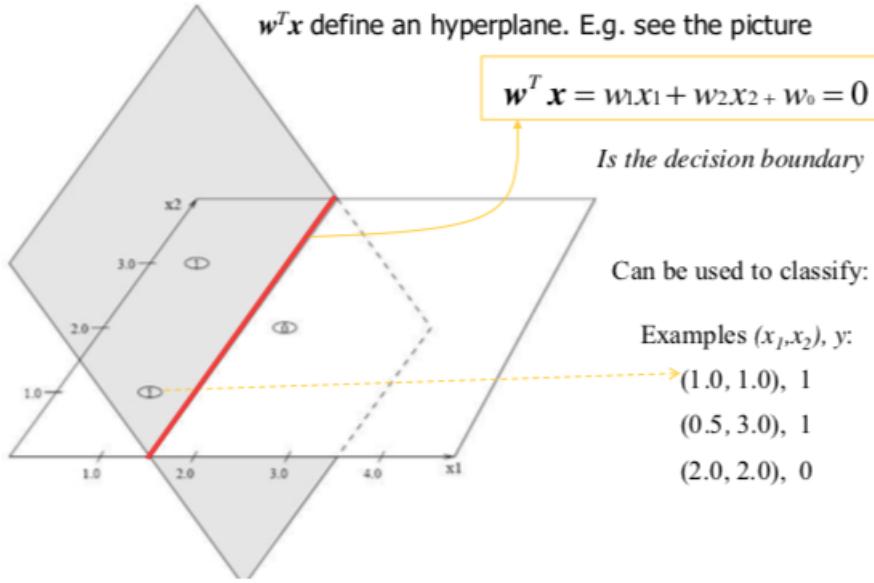


Figure 2.5: Geometrical view: hyperplane

A Geometrical view of our classifier is shown in figure 2.6

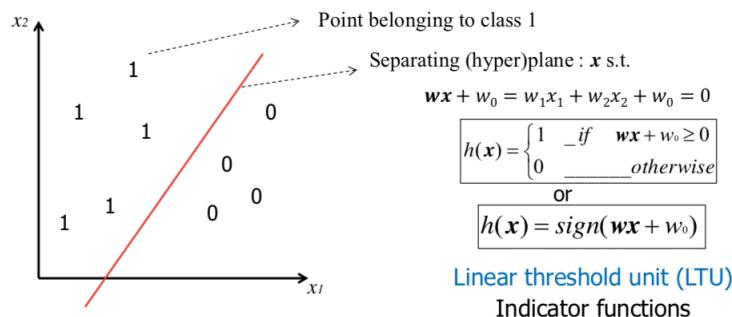
#### Classification by linear decision boundary:

The classification may be viewed as the allocation of the input space in decision regions (e.g. 0/1) and the linear decision boundary can solve a linearly separable problem.

#### Example 2.1

Linear separator on 2-dim instance space where our hypothesis space is composed by all the possible hyperplane (how the weight ( $\mathbf{w}$ ) change).

$$\mathbf{x} = (x_1, x_2) \in \mathbb{R}^2, f(\mathbf{x}) = 0/1 \text{ (or } -1/+1\text{)}$$



In general the solution is not unique: there are many possible hyperplanes separating, let's see some hyperplane properties and how the hyperplane change with different  $\mathbf{w}$  values.

#### Hyperplane properties:

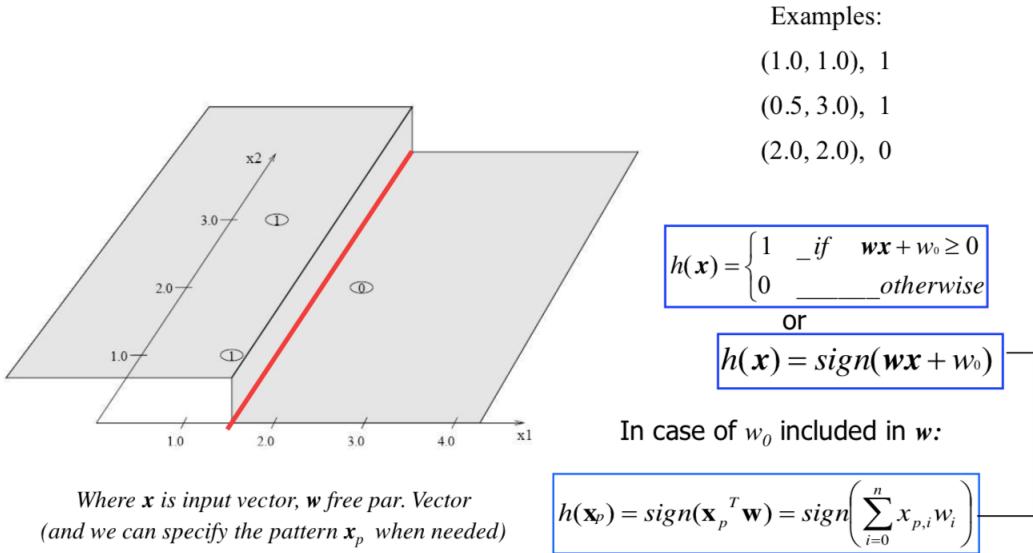
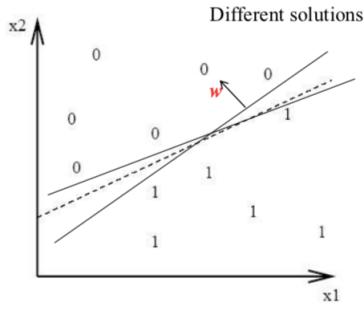


Figure 2.6: Geometrical view: hyperplane



- If  $w_0 = 0$  the line goes through the origin of the coordinate system.
- If  $n > 2 \rightarrow$  hyperplane
- Scaling freedom: the same hyperplane multiplying  $\mathbf{w}$  by K
- $\mathbf{w}$  is a vector orthogonal to the hyperplane, given  $\mathbf{x}_a, \mathbf{x}_b$  (belonging to the hyperplane):

$$\mathbf{x}_a^T \mathbf{w} + w_0 = 0 ; \mathbf{x}_b^T \mathbf{w} + w_0 = 0 \rightarrow \mathbf{w}^T (\mathbf{x}_a - \mathbf{x}_b) = 0 \rightarrow \text{orthogonal vectors}$$

- The best Hyperplane (the solution) is not unique.

### 2.2.1 Role of Threshold $w_0$

Consider the bias  $w_0$  in the LTU (Linear Threshold Unit). Asking for:

$$h(\mathbf{x}) = \mathbf{w}^T \mathbf{x} + w_0 \geq 0.$$

Is the same that:

$$h(\mathbf{x}) = \mathbf{w}^T \mathbf{x} \geq -w_0.$$

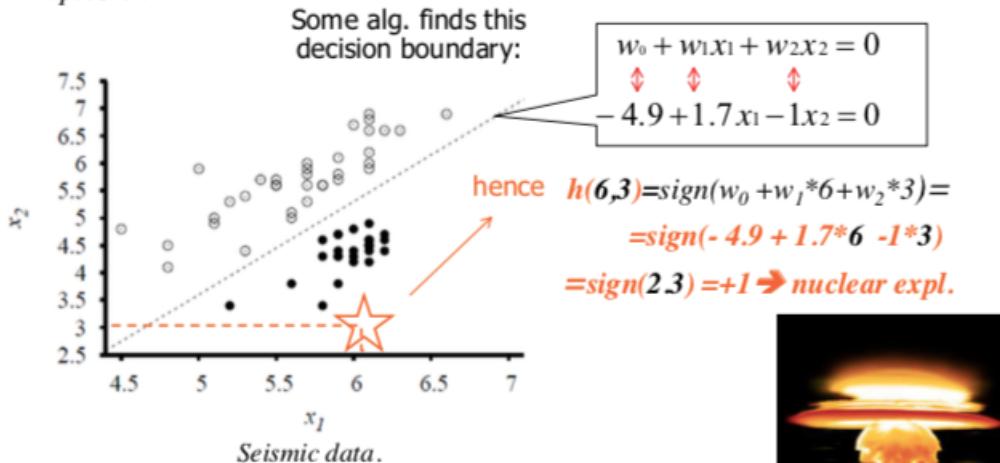
Wich  $-w_0$  is now assumed as the "threshold" value.

- The two form identify the same positive zone of the classifier.
- The second form emphasizes the role of the bias as threshold value to "activate" the +1 output of the classifier.

Here two examples:

(AIMA) Classify a new data  $(x_1, x_2)$

Find  $h$  s.t. given  $(x_1, x_2)$  return 0/-1 for Earthquakes and 1 for Nuclear Explosion



A. Micheli

1982-1990 Asia

Getting new examples is expensive;-)

32

Spam

- Find  $h(\text{mail}) + 1$  for spam, -1 not-spam
- Features  $\Phi(\text{mail})$  = words [0/1] or phrases ("free money") [0/1] or length [integer]
- e.g.  $\phi_k(\mathbf{x}) = \text{contain(word}_k)$  [bag of words representation]
- $w \rightarrow$  weight contribution of the input features to prediction
  - e.g. positive weight for "free money", negative for ".edu"
- $xw$  is the weight combination
- $h_w(x)$  provide the threshold to decide spam/not spam

$$h_w(\mathbf{x}) = \text{sign}\left(\sum_k w_k \phi_k(\mathbf{x})\right) > 0 \rightarrow +1 = \text{Spam!}$$



## 2.3 Learning Algorithms

A learning algorithm is divided into two types:

- **Eager:** Analyze the training data and construct an explicit hypothesis.
- **Lazy:** Store the training data and wait until a test data point is presented, then construct an ad hoc hypothesis to classify that one data point.

The linear model expected to construct an explicit hypothesis from the training set, so the learning algorithm for the linear model is **Eager**.

We are going to introduce 2 *learning algorithms* for the regression and for the classification task using a linear model, both based on *LMS*.

- A direct approach based on **normal equation** solution
- An iterative approach based on **gradient descent**

The learning algorithm has

We start redefining the learning problem and the loss for them (for 1 data and multidimensional inputs).

### The learning problem (classification tasks)

**Given** a set of  $l$  training example  $(\mathbf{x}_i, y_i)$  and a loss function (measure)  $L$ , we want to **find** the weight vector  $\mathbf{w}$  that minimizes the expected loss on the training data.

$$R_{emp} = \frac{1}{l} \sum_{i=1}^l L(h(\mathbf{x}_i), y_i)$$

For classification: Using a piecewise constant (over  $sign(\mathbf{w}^T \mathbf{x})$ ) for the loss can make this a difficult problem because it is not continuous and differentiable. Assume we still use the least squares (as for the regression case).

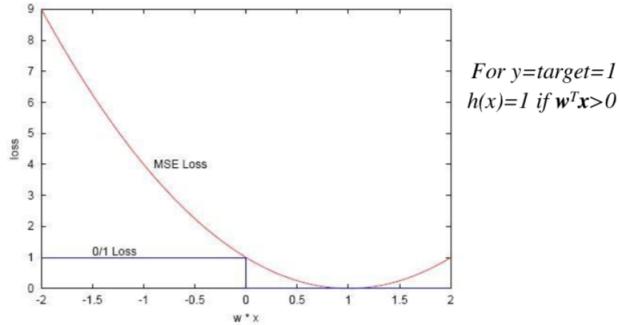


Figure 2.7: Example of Loss for the classification of a Positive instance. Both Loss satisfies the minimization of error.

Initially, we can make the optimization problem easier by replacing the original objective function  $\mathbf{L}$  by a smooth, differentiable function. For example, consider the mean squared error. See figure 2.7.

### Learning (a classifier) by Least Squares:

**Given** a set of  $l$  training example  $(\mathbf{x}_i, y_i)$ , **Find** optimal values for  $\mathbf{w}$  (for fitting of Training data) by using the **least squares** that minimize the residual sum of squares:

$$E(\mathbf{w}) = 1/l \sum_{i=1}^l (y_i - \mathbf{x}_i^T \mathbf{w})^2 = \|\mathbf{y} - \mathbf{X}\mathbf{w}\|^2$$

Min error: if  $y_i = 1$  then  $x_i^T \mathbf{w} \rightarrow 1$ ; if  $y_i = 0$  then  $x_i^T \mathbf{w} \rightarrow 0$

**Important:** In  $E(\mathbf{W})$  we do not use  $h(\mathbf{x})$ , as for regression, but to hold a continuous differentiable loss (because  $h(\mathbf{x}) = \text{sign}(\mathbf{w}\mathbf{x})$  for classification) we will use  $\mathbf{x}_i^T \mathbf{w}$

This is a *quadratic function* so the minimum always exists (but may be not unique). ( $X$  is a matrix  $l \times n$  with a row for each input vector  $\mathbf{x}_i$ ).

### 2.3.1 Normal equation and direct approach solution

Differentiating  $E(\mathbf{w})$  with respect to  $\mathbf{w}$  we get the normal equation (point with gradient of  $E$  w.r.t  $\mathbf{w} = 0$ ):

$$(\mathbf{X}^T \mathbf{X})\mathbf{w} = \mathbf{X}^T \mathbf{y}$$

*Proof.* Now we want to compute  $\frac{\partial E(\mathbf{w})}{\mathbf{w}_j} = 0$  ,  $j = 0, \dots, n$

$$E(\mathbf{w}) = \sum_{i=1}^l (y_i - \sum_{t=0}^n w_t x_{i,t})^2 = \sum_{i=1}^l (\delta_i(\mathbf{w}))^2 \quad (l \text{ patterns})$$

$$\begin{aligned} \frac{\partial E(\mathbf{w})}{\mathbf{w}_j} &= 2 \sum_{i=1}^l \delta_i(\mathbf{w}) \frac{\partial(\delta_i(\mathbf{w}))}{\partial \mathbf{w}_j} = 2 \sum_{i=1}^l \delta_i(\mathbf{w}) \frac{\partial(y_i - \sum_{t=0}^n w_t x_{i,t})}{\partial \mathbf{w}_j} = \\ &= 2 \sum_{i=1}^l \delta_i(\mathbf{w})(-x_{i,j}) = -2 \sum_{i=1}^l x_{i,j} \delta_i(\mathbf{w}) = -2 \sum_{i=1}^l x_{i,j} (y_i - \sum_{t=0}^n w_t x_{i,t}) = 0 \\ &\sum_{i=1}^l x_{i,j} y_i = \sum_{i=1}^l \sum_{t=1}^n w_t x_{i,t} x_{i,j} , \quad j = 0, \dots, n \end{aligned}$$

$$\mathbf{X}^T \mathbf{y} = (\mathbf{X}^T \mathbf{X})\mathbf{w}$$

□

So, if  $(\mathbf{X}^T \mathbf{X})$  is not singular the unique solution is given by:

$$\mathbf{w} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y} = \mathbf{X}^+ \mathbf{y}$$

Else the solution are infinite (satisfying the normal equation):

we can choose the min norm ( $\mathbf{w}$ ) solution.

**note:**  $(\mathbf{X}^+)$  is the Moore-Penrose pseudoinverse also if  $\mathbf{X}$  is not invertible)

#### Direct approach by SVD:

The Singular Value Decomposition can be used for computing the pseudoinverse of a matrix:

$$\mathbf{X} = \mathbf{U} \Sigma \mathbf{V}^T \implies \mathbf{X}^+ = \mathbf{V} \Sigma^+ \mathbf{U}^T.$$

Where  $\Sigma$  are the diagonals values.

Moreover we can apply directly SVD to compute  $\mathbf{w} = \mathbf{X}^+ \mathbf{y}$  obtaining the minimal norm (on  $\mathbf{w}$ ) solution of least squares problem.

### 2.3.2 Gradient descent

An iterative approach based on *gradient descent*: Previous derivation suggest the line to construct an iterative algorithm based on :

$$\frac{\partial E(\mathbf{w})}{\partial \mathbf{w}_j} = -2 \sum_{i=1}^l (y_i - \mathbf{x}_i^T \mathbf{w})(\mathbf{x}_i)_j = - \sum_{i=1}^l 2\delta_i x_{i,j}$$

Where

- $\mathbf{x}_i$ : i-th input pattern
- $y_i$ : the output for  $p$
- $\mathbf{w}$ : free parameters
- $l$ : numbers of examples
- $(\mathbf{x}_i)_j$ : component  $j$  of pattern  $i$

Gradient (ascent direction): we can move toward the minimum with a gradient descent (- gradient of  $E(\mathbf{w})$ ).

**Local search**: begins with initial weight vector. Modifies it iteratively to decrease up to minimize the error function (steepest descent).

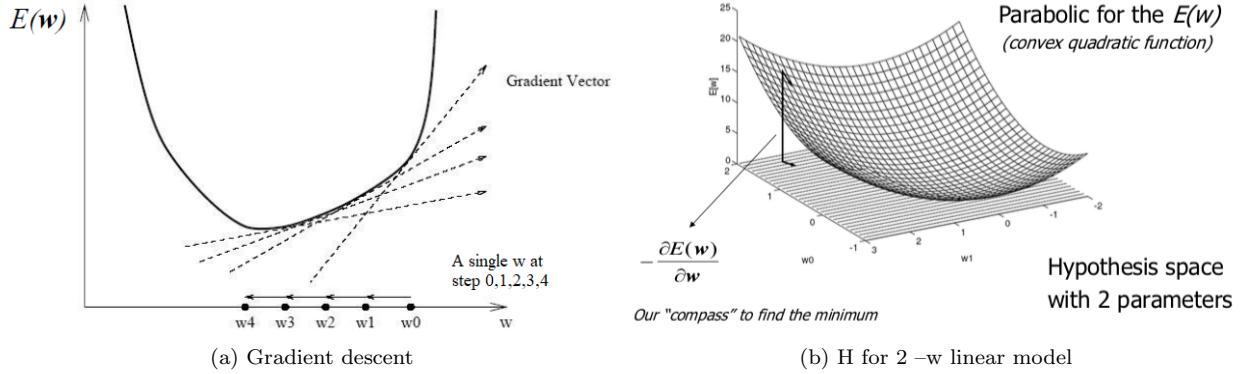


Figure 2.8: In the left we can see that choosing the direction  $-\frac{\partial E(\mathbf{w})}{\partial \mathbf{w}}$  we are moving to the minimum of  $E(\mathbf{w})$  (step by step).

### Delta Rule

A training rule whose key idea behind the delta rule is to use gradient descent to search the hypothesis space of possible weight vectors to find the weights that best fit the training examples.

The «movements» will be made iteratively according to the **Learning Rule**:

$$\mathbf{w}_{new} = \mathbf{w}_{old} + eta \cdot \Delta \mathbf{w}$$

where  $eta$  is the step size,  $0 < eta < 1$  or a value.  $\Delta \mathbf{w}$  is  $-\frac{\partial E(\mathbf{w})}{\partial \mathbf{w}}$  (vectorial).

**learning rate ( $\eta$ ) - eta** =: speed/stability trade-off and is the step size: can be (gradually) decreased to zero (guarantee convergence, avoiding oscillation around the min.): many variants will be introduced later.

In figure 2.9 is shown how the gradient descent change with different learning rate and figure 2.11 is shown how the learning curve can change.

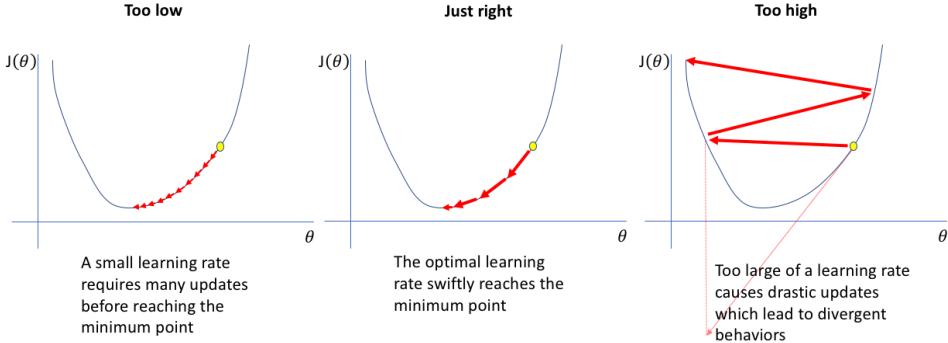


Figure 2.9: Different learning rate bring to different convergences speed and also different results.

### Gradient descent algorithm

- 1) Start with weight vector  $w_{\text{initial}}$  (small), fix  $\text{eta}$  ( $0 < \text{eta} < 1$ ).
  - 2) Compute  $\Delta w = -\text{"gradient of } E(w)\text{"} = -\frac{\partial E(w)}{\partial w}$  (for each  $w_j$ )
  - 3) Compute  $w_{\text{new}} = w_{\text{old}} + \text{eta} * \Delta w$  (for each  $w_j$ )  
where  $\text{eta}$  is the "step size" parameter
  - 4) Repeat (2) until convergence or  $E(w)$  is "sufficiently small"
- Learning rule

In the standard case we use  $\Delta w/l$ : least mean squares (when you divide by 1). It's good to normalize the value of the gradient, otherwise could be too large and could lead to oscillations (bad learning curve).

There are two versions of the algorithm:

- For **batch version** the gradient is the sum over all the  $l$  patterns (using  $p$ ):

$$\frac{\partial E(w)}{\partial w_i} = -2 \sum_{p=1}^l (y_p - \mathbf{x}_p^T \mathbf{w}) x_{p,i}$$

So, to calculate the gradient of the cost function, we need to sum the cost of each pattern. If we have 3 million patterns, we have to loop through 3 million times or use the dot product.

Note that:

- $x_{p,i}$  is the component  $i$  of pattern  $p$
- 2 is constant that can be ignored to develop the algorithm
- we typically use *LMS* (use  $1/l$  in front of the sum)
- provide a more "precise" evaluation of the gradient over a set of  $l$  data
- We upgrade the weights after this sum

- For the **on-line/stochastic version** we upgrade the weights with the error that is computed for each pattern.

$$\frac{\partial E_p(w)}{\partial w_i} = -2(y_p - \mathbf{x}_p^T \mathbf{w}) x_{p,i}$$

In SGD weights are updated upon examining each training example so, we only use 1 example for each learning step. Because it's using only one example at a time, its path to the minima more random than that of the batch gradient. Usually, before for-looping, you need to randomly shuffle the training examples.

- We will see intermediate cases later (as **mini-batch**): Mini-batch gradient descent uses n data points (instead of 1 sample in SGD) at each iteration.

Here an example showing how the trajectory change with different gradient descent algorithm:

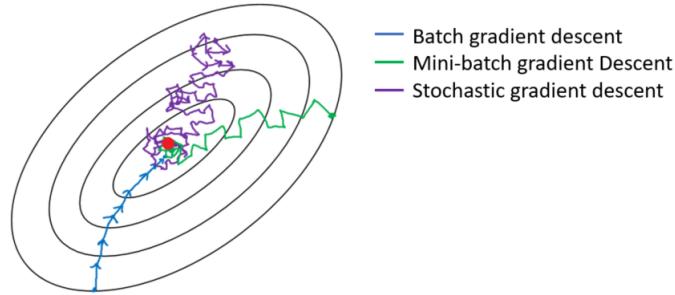


Figure 2.10: Gradient descent variants trajectory towards minimum

**Learning curve examples:** the curve can change with different gradient algorithm and different value of the learning rate:

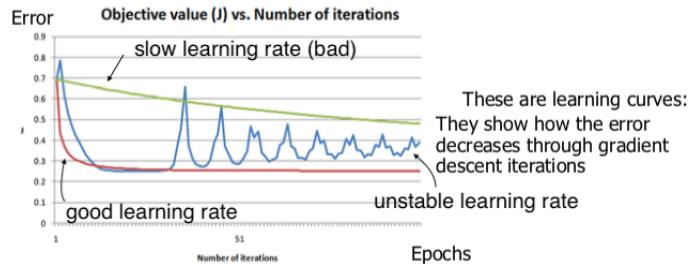


Figure 2.11: Learning curve examples

### Gradient descent as Error correction rule

$$\Delta w_j = \sum_{p=1}^l (y_p - \mathbf{x}_p^T \mathbf{w}) (\mathbf{x}_p)_j$$

$$\mathbf{w}_{new} = \mathbf{w} + \eta \cdot \Delta \mathbf{w}.$$

This is an “error correction” rule (Widrow-Hoff) that change the  $w$  proportionally to the error (target-output):

For example:

- $(target - output) = err = 0 \rightarrow$  no correction
- $(input_j > 0) if err + (output is too low) :$

$increase w_j \rightarrow increase output \rightarrow less err$

- $(input_j > 0) if err - (output is too high) :$

$decrease w_j \rightarrow reduce output \rightarrow less err$

- ( $input_j < 0$ ) if err + (output is too low) :

*decrease  $w_j \rightarrow increase output \rightarrow less err$*

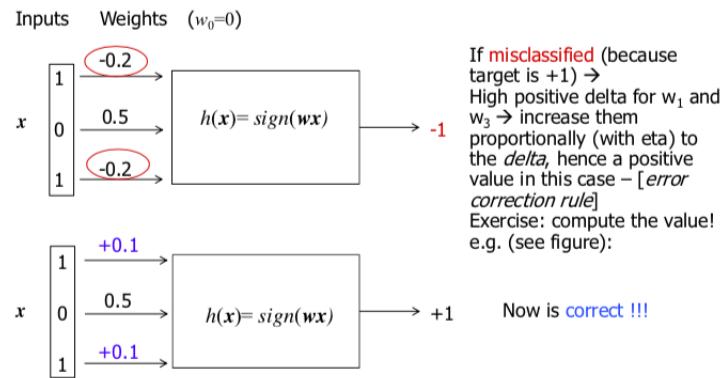
- ( $input_j < 0$ ) if err - (output is too high) :

*increase  $w_j \rightarrow reduce output \rightarrow less err$*

It allow us to search through an *infinite hypothesis* space and it can be easily always applied for *continues H* and differentiable loss.

**NOTE:** Is the gradient descent efficient? Many improvement are possible: Newton and quasi-newton methods, Conjugate Gradient, ...

Here and example of Delta-W as Error Correction Learning rule:



### 2.3.3 Summarizing

- Model trained (on tr set) with LS (LMS) on  $\mathbf{wx}$  by the simple gradient descent algorithm used for linear regression
- Model used for classification applying the threshold function  $h(\mathbf{x}) = sign(\mathbf{wx})$
- The error can be computed as classification error or number of misclassified patterns (not only by the Mean Square Error)

$$L(h(\mathbf{x}_p), d_p) = \begin{cases} 0 & \text{if } h(\mathbf{x}_p) = d_p \\ 1 & \text{otherwise} \end{cases} \quad mean\_err = \frac{1}{l} \sum_{i=1}^l L(h(\mathbf{x}_i), d_i) \quad num\_err$$

- ACCURACY = mean of correctly classified =  $(l - num\_err)/l$

## 2.4 Linear model on a classification problem

Let's analyze the problem shown in figure 2.12a problem and let's apply the linear model on the training data set.

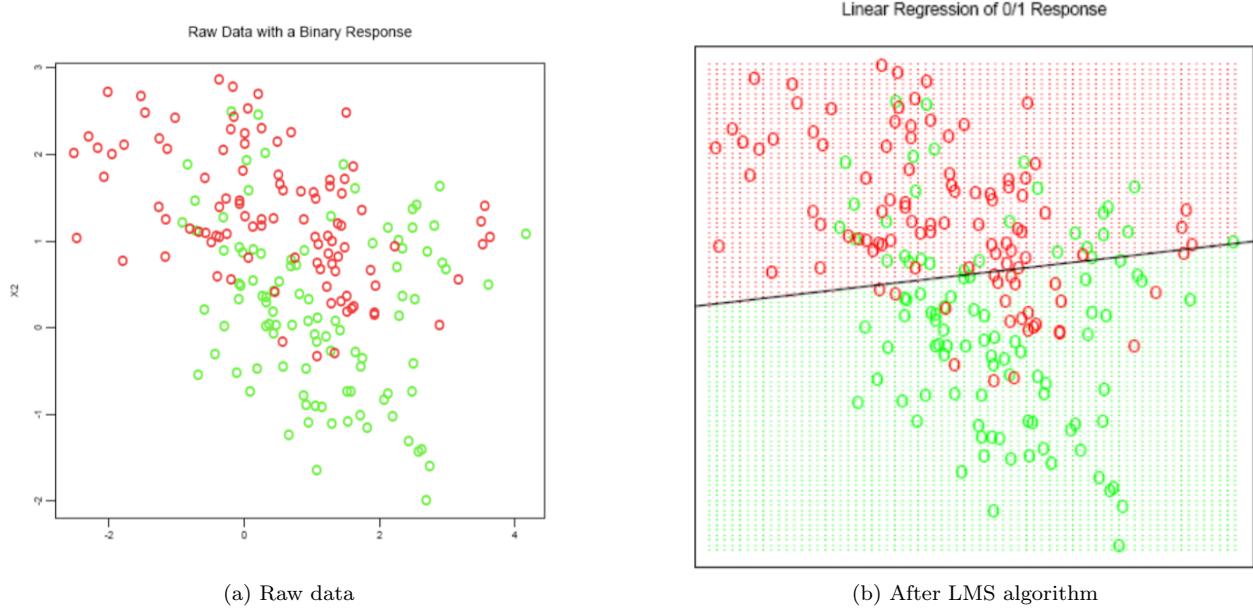


Figure 2.12: Solution of a classification example with LMS

A classification example in two dimensions. The classes are coded as a binary variable. In figure 2.12b we can see the result of the linear model: The line is the decision boundary defined by  $\mathbf{x}^T \mathbf{w} = 0.5$ .

$$h(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{x}^T \mathbf{w} > 0.5 \\ 0 & \text{otherwise} \end{cases}$$

The decision boundary is  $\{\mathbf{x} \mid \mathbf{x}^T \mathbf{w} = 0.5\}$  is linear (and seems to make many errors on the training data). Is it true?

**Good or bad approximation:** Possible scenarios (we know the true target function!):

- Scenario 1: The data in each class are generated from a Gaussian distribution with uncorrelated components, same variances, and different means.  
In this case  $\Rightarrow$  the linear regression rule (by LS) is almost optimal (is the best one can do). The region of overlap is inevitable (due to errors in the input data).
- Scenario 2: The data in each class are generated from a mixture of 10 gaussians in each class.  
In this case  $\Rightarrow$  the linear model is far too rigid: next models for it!

## 2.5 Linear Model in ML: inductive bias (Mitchell style)

- Language bias: the  $H$  is a set of linear functions (may be very restrictive and rigid)
- Search bias: ordered search guided by the Least Squares minimization goal
  - For instance we could prefer a different method to obtain a restriction on the values of parameters, achieving a different solutions with other properties...

- It shows that even for a “simple” model there are many possibilities. We still need a principled approach! (see theory of ML)...

## 2.6 Linear regression (in statistics)

In statistics, **linear regression** is used for two things:

- to construct a simple formula that will predict a value or values for a variable given the value of another variable.
- to test whether and how a given variable is related to another variable or variables.

Statistical Parametric models: note that, in general, “**linear**” does not refer to this straight line, but rather to the way in which the regression coefficients occur in the regression equation. (See next for “linear basis expansion”).

**NOTE:** Least squares corresponds to the maximum likelihood criterion if the experimental errors have a normal distribution.

## 2.7 Linear model (in ML): Inductive Bias (alla Mitchell)

In the Linear model we have two Bias:

- **Language bias:** the  $H$  is a set of linear functions (may be very restrictive and rigid)
- **Search bias:** ordered search guided by the Least Squares minimization goal: for instance we could prefer a different method to obtain a restriction on the values of parameters, achieving a different solutions with other properties...

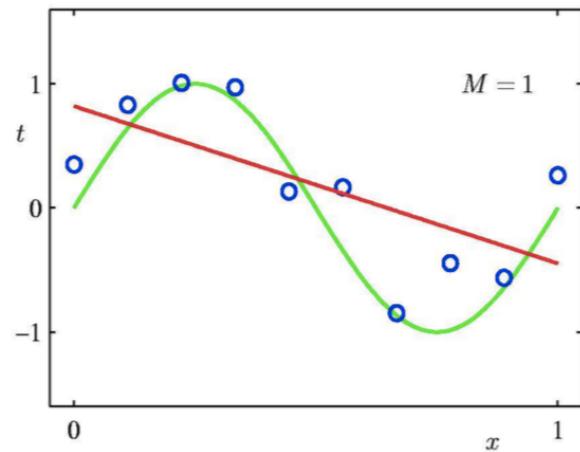
It show that even for a “simple” model there are many possibilities. We still need a principled approach! (see theory of ML)...

## 2.8 Limitations

This linear model has some limitation: It's a **rigid model**.

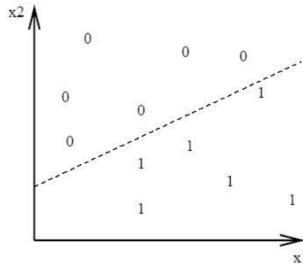
### ■ Regression tasks for non linear problems

In this case we have a very poor solution, a linear model can't fit a non linear problem! we have to find a solution for it!



## ■Classification tasks

- In geometry, two sets of points in a two-dimensional plot are **linearly separable** when the two sets of points can be completely separated by a single line.
- In general, two groups are linearly separable in  $n - \text{dimensional}$  space if they can be separated by an  $(n - 1) - \text{dimensional}$  hyperplane.
- The linear decision boundary can provide exact solutions only for linearly separable sets of points.



### Example: Conjunctions

We can represent conjunctions by the linear models:

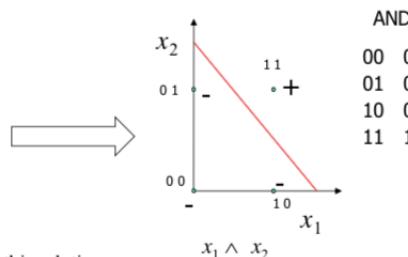
$$4 \text{ var.: } x_1 \wedge x_2 \wedge x_3 \wedge x_4 \leftrightarrow y$$

- $1 \ x_1 + 1 \ x_2 + 0 \ x_3 + 1 \ x_4 \geq 2.5$

In the plot:

$$2 \text{ var.: } x_1 \wedge x_2$$

- $1 \ x_1 + 1 \ x_2 \geq 1.5$



w can be learned to find this solution

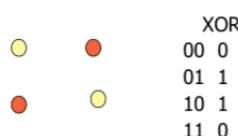
### Example: 3 point

Given 3 points, we can find a separation plane only if they are not aligned, otherwise no (3 aligned points with 0 in the middle and others 1):



### Example: 4 points

Given 4 points we can't always find a separation plane (we can find a labeling such that the linear classifier fails to be perfect), e.g xor:



## 2.9 A generalization

The linear model is a very rigid model, here we will show a basis expansion. This allow to get more **Flexibility**.

### ■Regression task

Basis transformation(**linear basis expansion**) :

$$h_w(\mathbf{x}) = \sum_{k=0}^K w_k \phi_k(\mathbf{x})$$

Augment the input vector with additional variables ( $K > n$ ) which are transformations of  $\mathbf{x}$  according to a function  $\phi_k : R^n \rightarrow R$ .  $\phi$  can be every function.

E.g:

- Polynomial representation of  $x$ :  $\phi(x) = x_j^2$  or  $\phi(x) = x_j x_i$ , or other functions
- Non-linear transformation of single inputs:  $\phi(x) = \log(x_j)$ ,  $\phi(x) = \text{root}(x_j)$ , ...
- Non-linear transformation of multiple input:  $\phi(x) = \|x\|$
- Splines, ...

This generalization is called: **dictionary** approaches and the model is linear in the parameters (also in phi, not in x!), so we can use the same learning algorithm as before!

**Example:**

- 1-dim  $x$  :  $\phi_j(x) = x^j$  (1 - dim polynomial regression ( $K = M$ )):

$$h(\mathbf{x}) = w_0 + w_1 x + w_2 x^2 + \cdots + w_M x^M = \sum_{j=0}^M w_j x^j$$

- any other,  $\phi(\mathbf{x}) = \phi([x_1, x_2, x_3])$ :

$$h(\mathbf{x}) = w_1 x_1 + w_2 x_2 + w_3 \log(x_2) + w_4 \log(x_3) + w_5 (x_2 x_3) + w_0$$

For *classification task* we add sign before the sum.

- **PROS:** Can model more complicated relationships (than linear). It is more expressive with more flexibility.
- **CONS:** With *large* basis of functions, we easily risk *overfitting*, hence we require methods for *controlling the complexity* of the model. Furthermore:
  - Phi are fixed before observing training data, it's hard to decide which  $\phi$  will be good for our data! (versus adaptive /non-linear in parameters e.g. in Neural Network)
  - *Curse of dimensionality* (the volume of the problem space increases so fast that the available data become sparse).

## 2.10 Improvements

### 2.10.1 How to control model complexity? Regularization

#### ■Ridge regression (Tikhonov regularization)

smoothed model → e.g. lower variance

$$\begin{aligned}
E(\mathbf{w}) &= \sum_{i=1}^l (y_i - \mathbf{x}_i^T \mathbf{w})^2 + \lambda \|\mathbf{w}\|^2 && \text{Regularization/penalty term} \\
\text{Loss} & & & \\
& & \downarrow & \\
& \boxed{\lambda \|\mathbf{w}\|^2} & & \\
& & \text{Lambda: regularization parameter} \\
& & (\text{a small positive value chosen by the "model selection" phase}) \\
\mathbf{w} &= \boxed{(\mathbf{X}^T \mathbf{X} + \lambda \mathbf{I})^{-1} \mathbf{X}^T \mathbf{y}} & & \text{For the direct approach: this matrix is always invertible} \\
& & & \\
\text{In terms of gradient approach: weight decay} & & & (\text{basically add } 2\lambda \mathbf{w} \text{ to the gradient}) \\
& & \mathbf{w}_{\text{new}} = \mathbf{w}_{\text{old}} + \eta * \Delta \mathbf{w} - 2\lambda \mathbf{w}_{\text{old}} &
\end{aligned}$$

Figure 2.13: Figura sbagliata...

**Note:** For the objective function we use here the name Loss (used for the model training cost function) to distinguish from the Error E (useful to evaluate the model error and used for the data term inside this Loss). Hence, differently from previous assumptions the two terms are not more equivalent in our use (in the course).

**Lambda ( $\lambda$ ) regularization parameter:**

$$0 \leq \lambda < 1$$

Possible to add constraints to the sum of value of  $|w_j|$  favouring "sparse" models e.g. with less terms due to weights  $w_j = 0$  (i.e. less complex solutions): ridge regression [or lasso, et al. (by different norms)]

- The penalty term *penalizes high value of the weights* and tends to drive all the weights to smaller values (some weights values can go even to zero).
- It *implements* a control of the model complexity
- This leads to a model with *less VC-Dim.*
- $\lambda$  values can rule the underfitting/overfitting cases.

Tikhonov regularization can be applied for every function and allow us to control the VC-dim. It's better to have a big H space and then control the search bias with  $\lambda$ .

**Remember:** Can be applied to any kind of function, in this way you easily understand which model is the simplest (just with one more parameter  $\lambda$ ). This move the complexity to the **Search Bias** instead of **Language Bias!**

■ **Example of control of model complexity:**

Let's suppose to have a regression task and we will use this  $h(\mathbf{x})$ :

$$h(\mathbf{x}) = w_0 + w_1x + w_2x^2 + \cdots + w_Mx^M = \sum_{j=0}^M w_jx^j$$

$$x : \phi_j(x) = x^j \text{ (1 - dim polynomial regression (} M = 9 \text{))}$$

Let's see how we can control the complexity of the model:

- in figure 2.14a we can see the case where  $\lambda = 0$  and there is no regularization. In this case how  $h(\mathbf{x})$  is in overfitting and the error  $E(w) = 0$  on the training set. This model is too complex and is able to fit the noise too. (we have to control the complexity of the model in this case)
- in figure 2.14b we use a small positive lambda ( $\lambda = 0.0000000152$ ). The model has been regularized it and the VC-dim has been reduced too. This model seems to works much better.
- in figure 2.14c we use a very high lambda, close to 1 ( $\ln \lambda = 0$ ) and the model goes in underfitting.

From the three previous cases we understand that we need a trade-off and we need to find the right lambda value that does not make us go underfitting or overfitting.

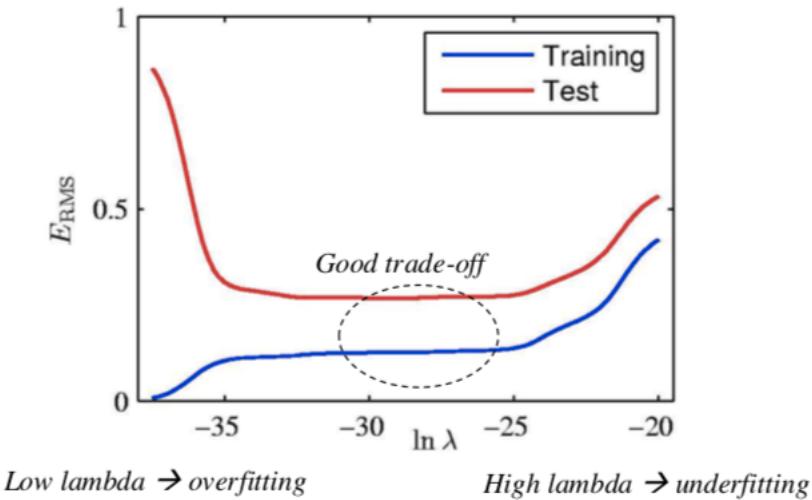


Figure 2.15: Regularization:  $E_{RMS}$  vs  $\ln \lambda$

In figure 2.15 we can see how the  $E_{RMS}$  change with different value of  $\lambda$  and figure 2.16 shows how the value of weights change with different value of  $\lambda$ .

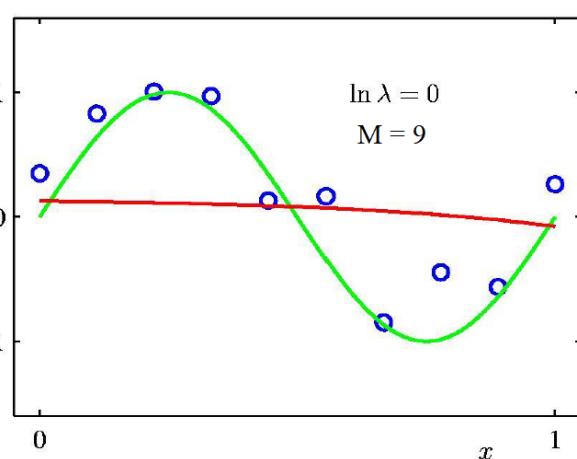
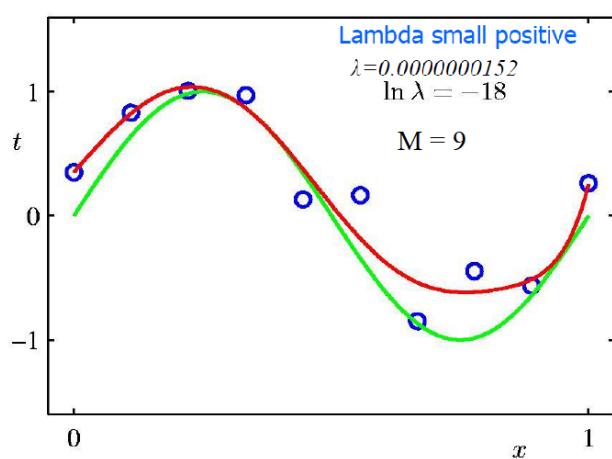
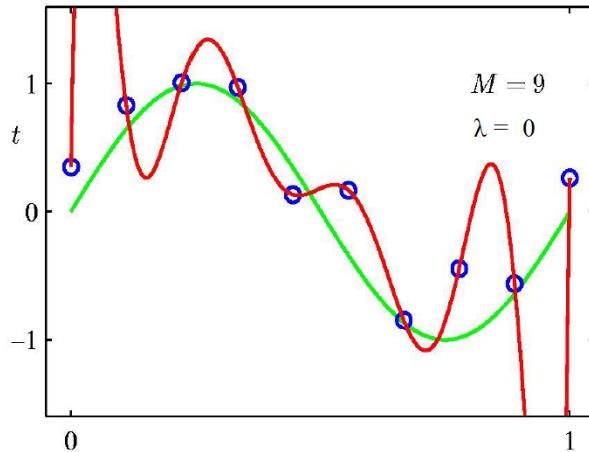


Figure 2.14: 9th Order Polynomial with control of complexity

	$0 \text{ lambda}$	$\ln \lambda = -\infty$	$\ln \lambda = -18$	$\ln \lambda = 0$ <span style="color: blue;">Very high lambda</span>
$w_0^*$		0.35	0.35	0.13
$w_1^*$		232.37	4.74	-0.05
$w_2^*$		-5321.83	-0.77	-0.06
$w_3^*$		48568.31	-31.97	-0.05
$w_4^*$		-231639.30	-3.89	-0.03
$w_5^*$		640042.26	55.28	-0.02
$w_6^*$		-1061800.52	41.32	-0.01
$w_7^*$		1042400.18	-45.95	-0.00
$w_8^*$		-557682.99	-91.53	0.00
$w_9^*$		125201.43	72.68	0.01

Figure 2.16: Polynomial Coefficients

### 2.10.2 Other Regularization Technology for Linear Models

There is other technology used for regularization that we will introduce in later sections:

- Ridge regression ( $\|\cdot\|_2$ )
- Lasso ( $\|\cdot\|_1$ )
- Elastic nets (use both  $\|\cdot\|_1$  and  $\|\cdot\|_2$ )

The L2 norm penalizes the square value of the weight and tends to drive all the weights to smaller values. On the other hand, the L1 norm penalizes the absolute value of the weight and tends to drive some weights to exactly zero (while allowing some weights to be large) → toward feature selection!

**NOTE:** Unfortunately  $\|\cdot\|_1$  (absolute value) introduce a non differentiable so the loss needs other approaches.

### 2.10.3 Others Improvements

- Inputs with added noise (data augmentation)
- Derived inputs: a small number of new variables is used in place of the  $x$  inputs, which are a linear combination of  $x$ .
  - *Principal Component Regression*
  - *Partial Least Squares*

## 2.11 Multi-class task

There are two very simple approaches for multi-class:

- **OVA (one-vs-all):** a discriminant function for each class, built on top of real-valued binary classifiers:
  - train  $K$  different binary classifiers, each one trained to distinguish the examples in a single class from the examples in all remaining classes.
  - to classify a new example, the  $K$  classifiers are run, and the classifier which outputs the largest (most positive) value is chosen.

$$h(\mathbf{x}) = \arg \max_i h_i(\mathbf{x})$$

e.g. Class 1-of-K rep: red, green, blue → (0,0,1), (0,1,0), (1,0,0). → solve 3 linear models.

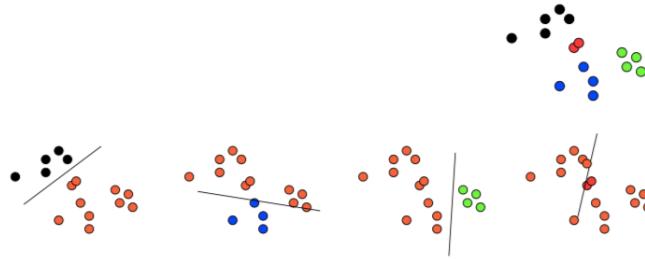
- **AVA (all-vs-all = one-versus-one):** Each classifier separates a pair of classes. Build  $K(K - 1)$  classifiers K-way multiclass problem, one classifier to distinguish each pair of classes  $i$  and  $j$ .
  - to classify a new example, all the classifiers are run, and the winner is the one with the max sum of outputs versus all the other classes OR the class with most votes

$$h(\mathbf{x}) = \arg \max_i (\sum_j h_{ij}(\mathbf{x}))$$

- training data set for each classifier is much smaller

OVA, AVA suffers from ambiguities in that some regions of its input space may receive the same number of votes.

**Criticism:** The problem can become not easy



- Masking: classes can be masked by others (for high K)
- A wide array of more sophisticated approaches for multiclass classification exists ...
- Some models can deal directly with multi-output

## 2.12 Other learner models for classification

- Linear Discriminant Analysis (also multi-class)
- Logistic regression  
 $P(y|x)$  starting from modeling the class density as a known density

## Extensions: ML Models (pro future) (#)



In ML course:

- Perceptron (Rosenblatt 1958, biological inspiration):
  - “minimize (only) misclassifications” algorithm
  - basis for Neural Networks (set of units with layers)
  - Adaptive basis expansions (*phi learned by training*)
    - Feature representation learning in each layer (deep learning concept)
  - Gradient descent approach for learning
- SVM (Vapnik 1996):
  - regularization via the concept of maximum margin: Maximize the gap (margin) between the two classes on the training data.
  - enlarge the feature space via basis expansions (e.g. polynomials).
- NN and SVM models realize (also) a flexible ***non-linear*** approximation for classification and regression problems

# ML Course structure

## Discussion on Linear Model



In the *file rouge* of ML, 2 main concepts up to now:

- Basis expansion → (implement) more flexibility
- Regularization → (implement) control of complexity
- The cases of the *linear models* provided an *instance* rooted in the classical mathematical approaches but we will find again these concepts, by different models and implemented in different/similar forms, in the modern ML (e.g. for NN & SVM in our course)!
- Now we move on the other extreme toward a very flexible approach